

What efficacy and safety profiles can we expect

*Mathematical and Computational Biology in Drug Discovery
(MCBDD) Module IV*

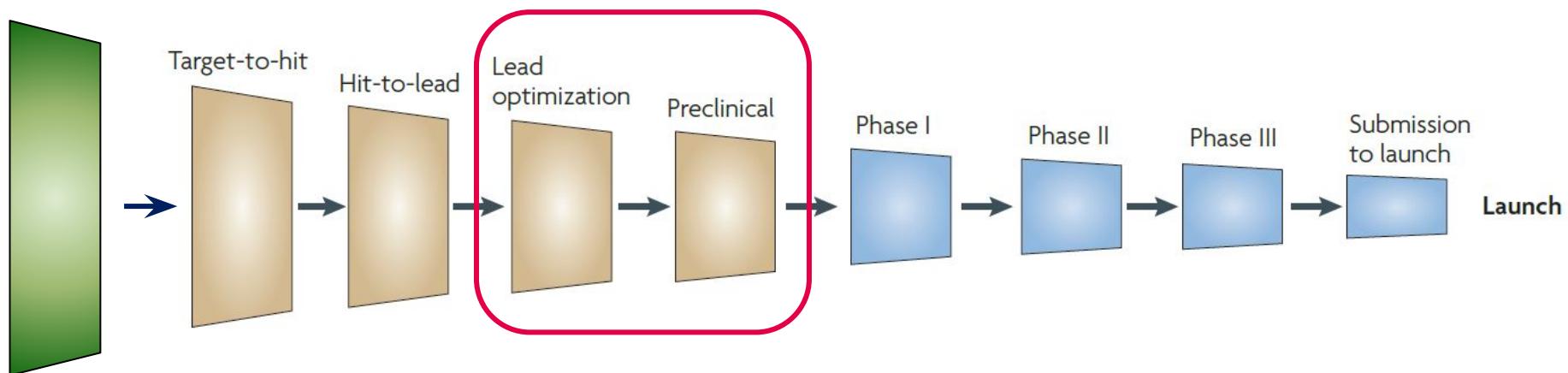
*Dr. Jitao David Zhang
April-May 2021*

Outline of Lecture 9

- Understanding pharmacology and toxicology with *in vitro*, *in vivo*, and *in silico* models
- Cell-type specific response to drugs
- Single-cell RNA sequencing for disease understanding and drug discovery

Where are we now

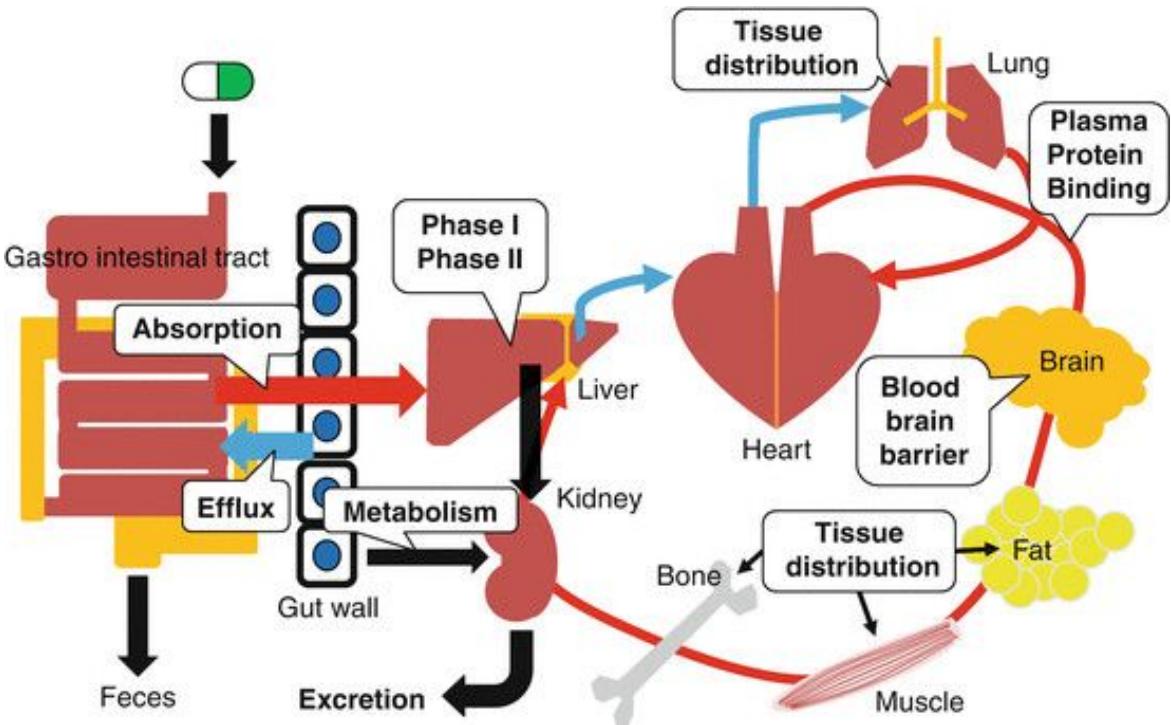
Target identification & assessment



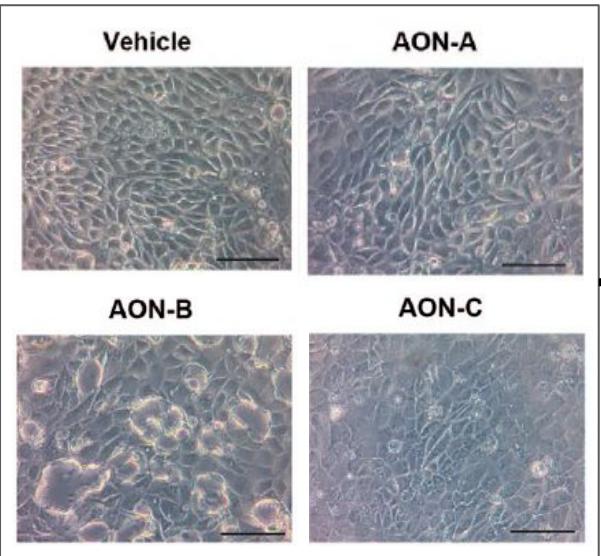
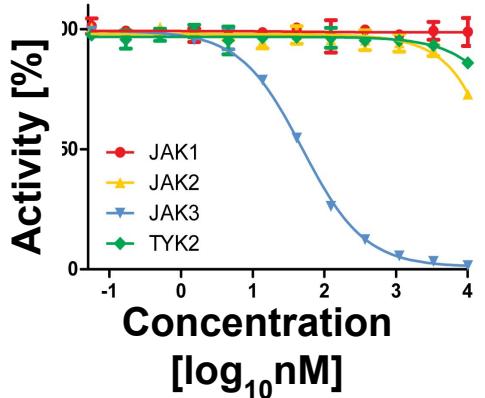
Goal: we want to select **one compound** from a few (~ 10^2 - 10^0) for entry in human.

Factors that affect efficacy and safety profiles

- Absorption
- Distribution
- **Pharmacology**
- **Toxicology**
- Metabolism
- Excretion

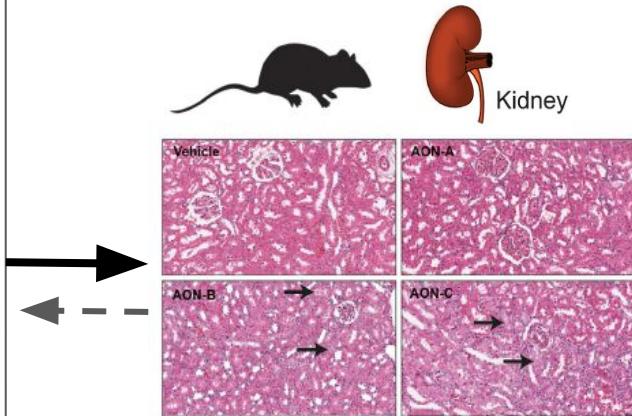


Classical workflow of efficacy and toxicity assessment



**Cellular assays
(*in vitro*)**

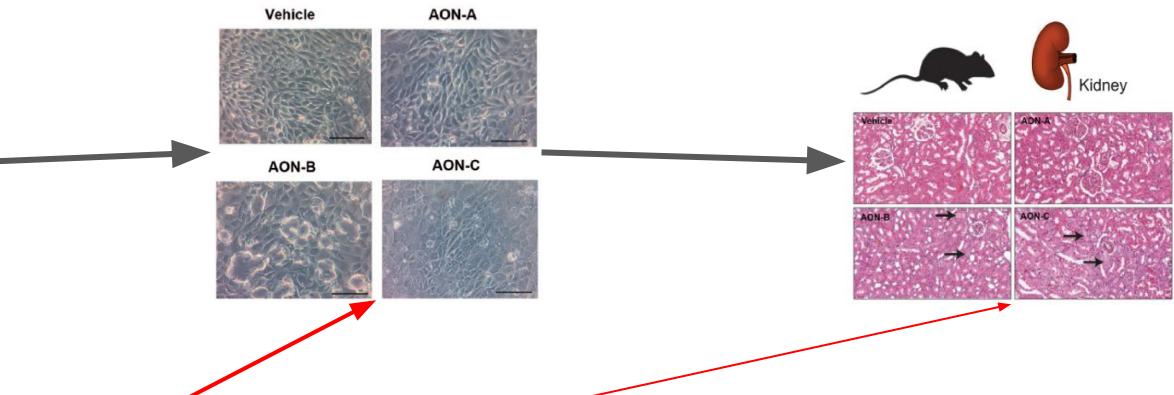
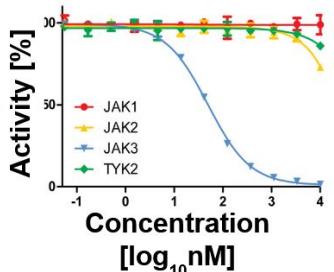
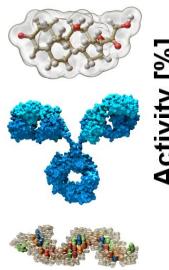
**Biochemical &
biophysical
assays**



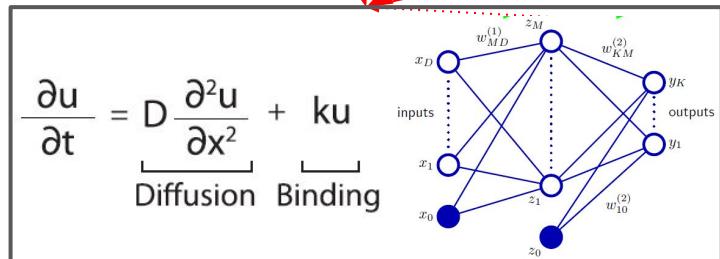
**Animal
experiments
(*in vivo*)**

→ Usual workflow
 ← - - Assay development

Computational methods empower efficacy and toxicity assessment

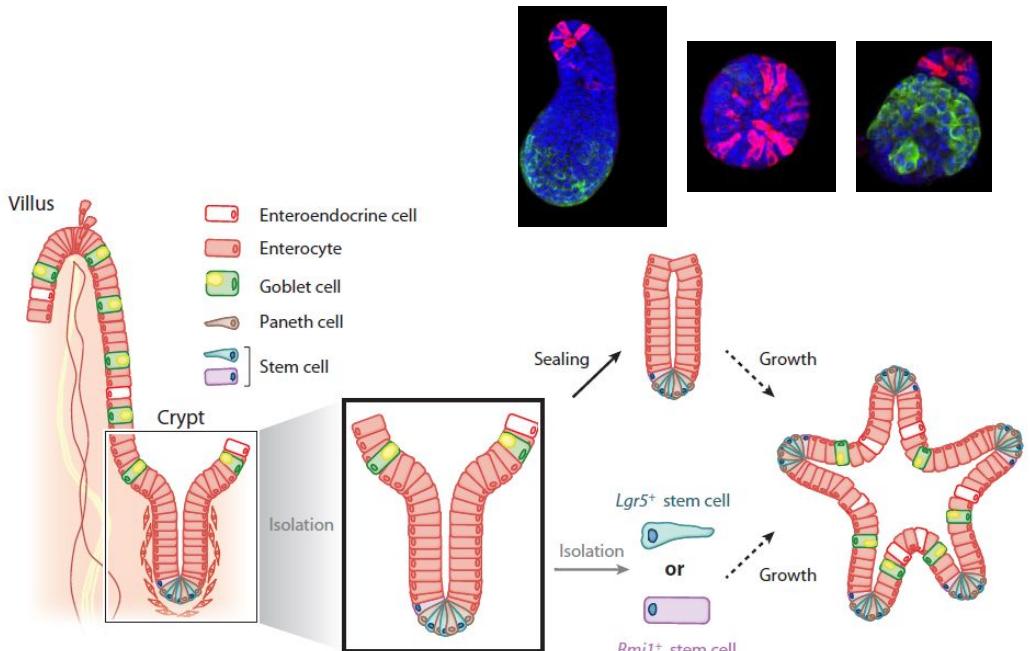
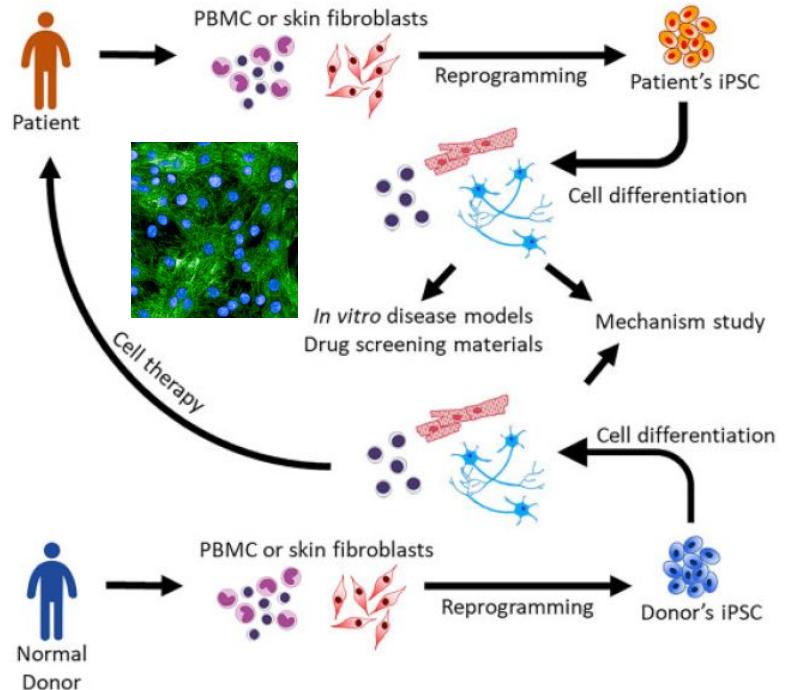


High-throughput technologies (omics, microscopy, etc.)



Mechanistic and statistical models

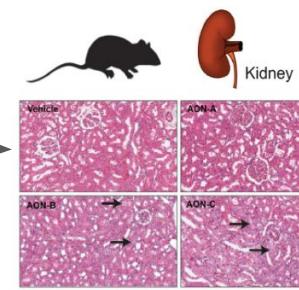
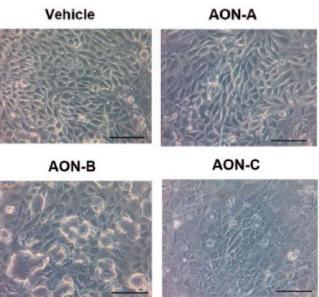
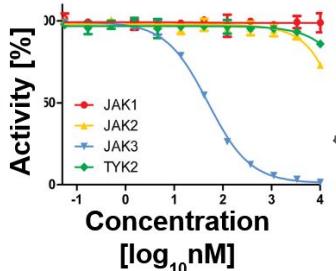
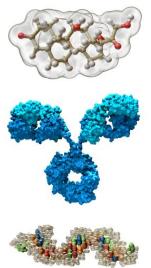
Stem cells and organoids empower efficacy and toxicity assessment



Small-intestinal organoids

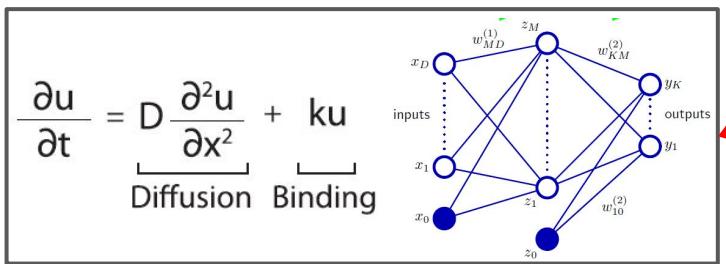
Induced pluripotent stem-cells

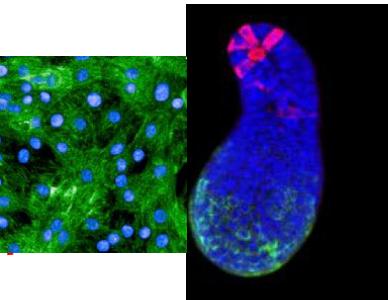
Computational methods and novel biological models empower efficacy and toxicity assessment



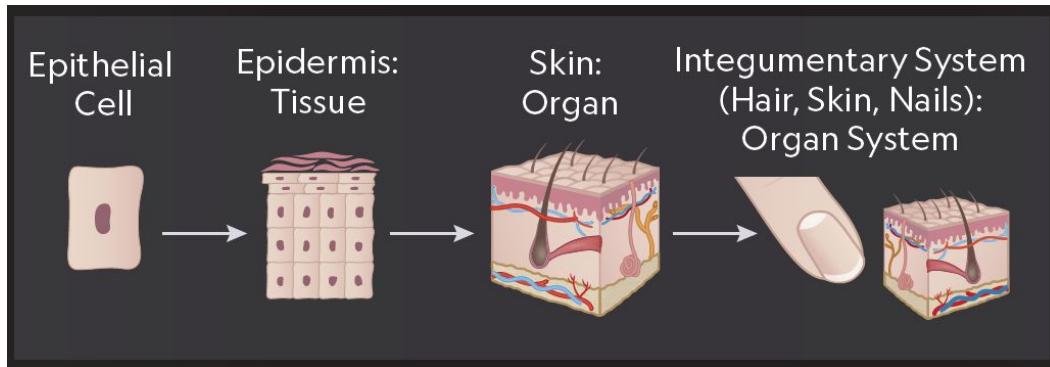
$$\frac{\partial u}{\partial t} = D \frac{\partial^2 u}{\partial x^2} + ku$$

Diffusion Binding





Complexity Increases Through a System

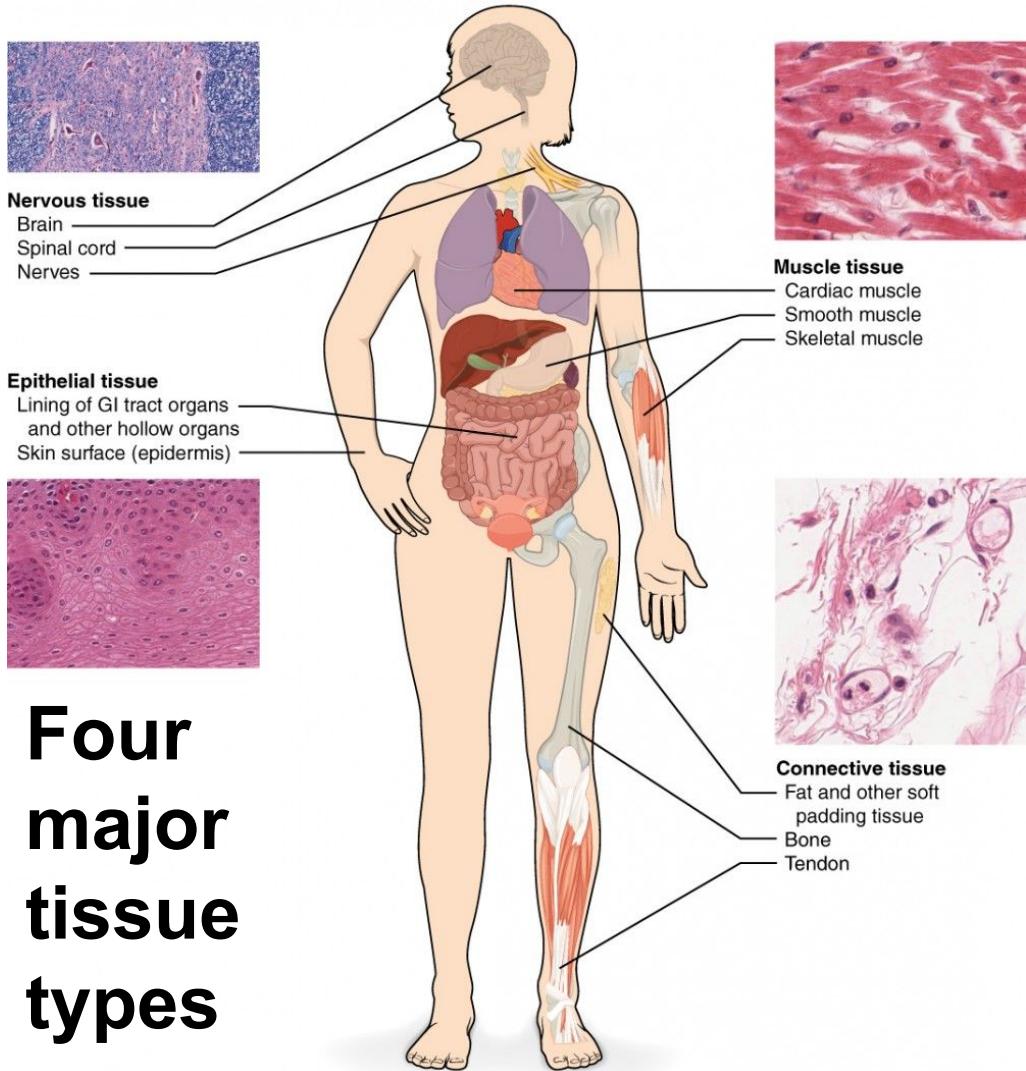
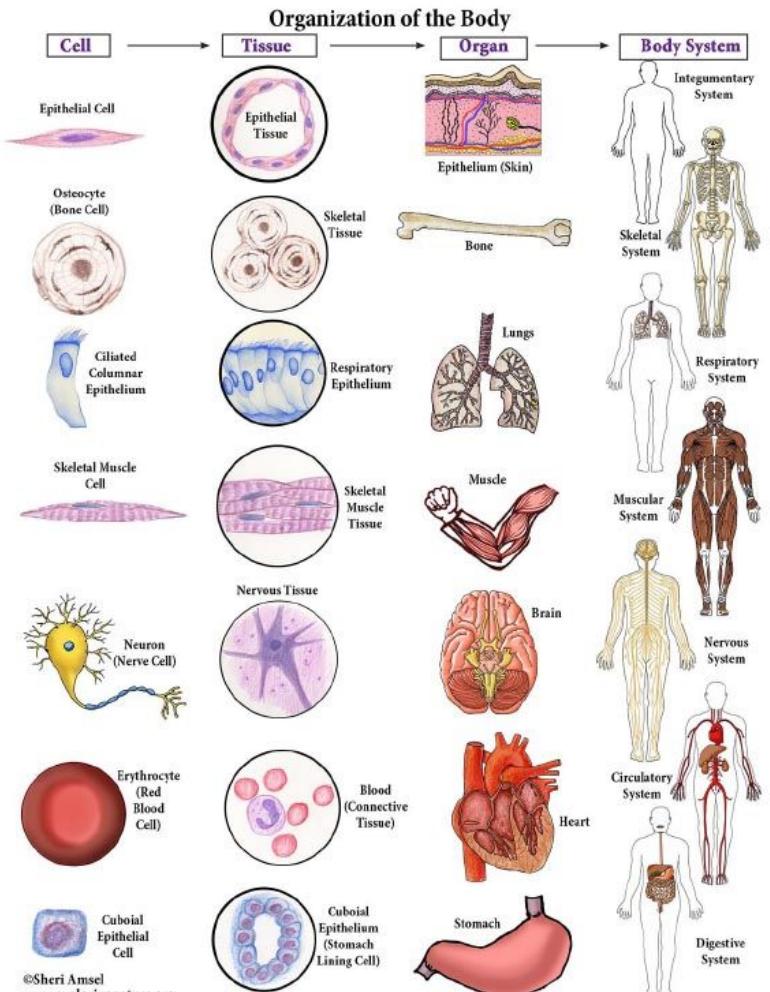


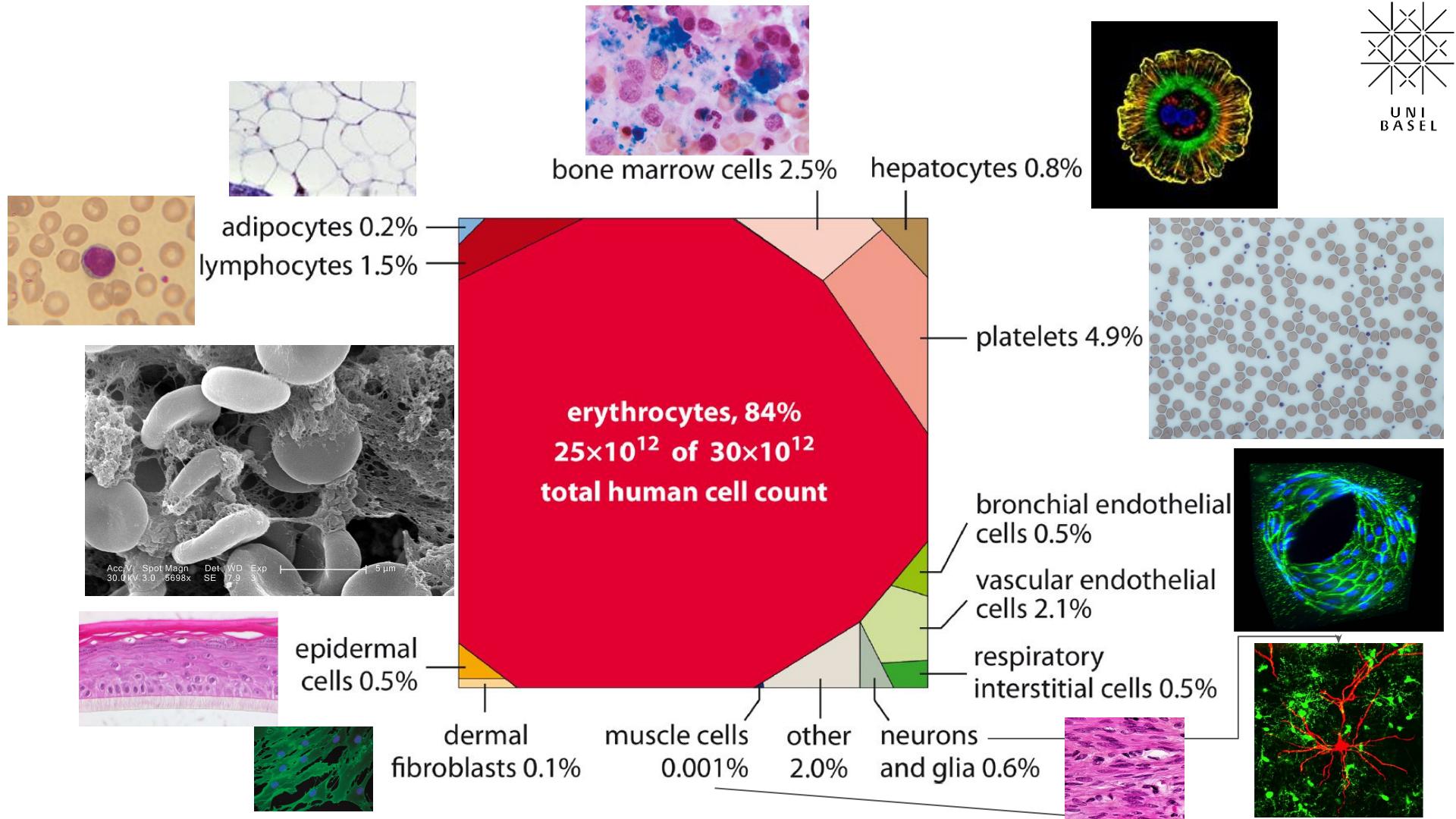
Cells: basic building blocks, variable morphologies and functions

Tissues: groups of specialized cells that communicate and collaborate

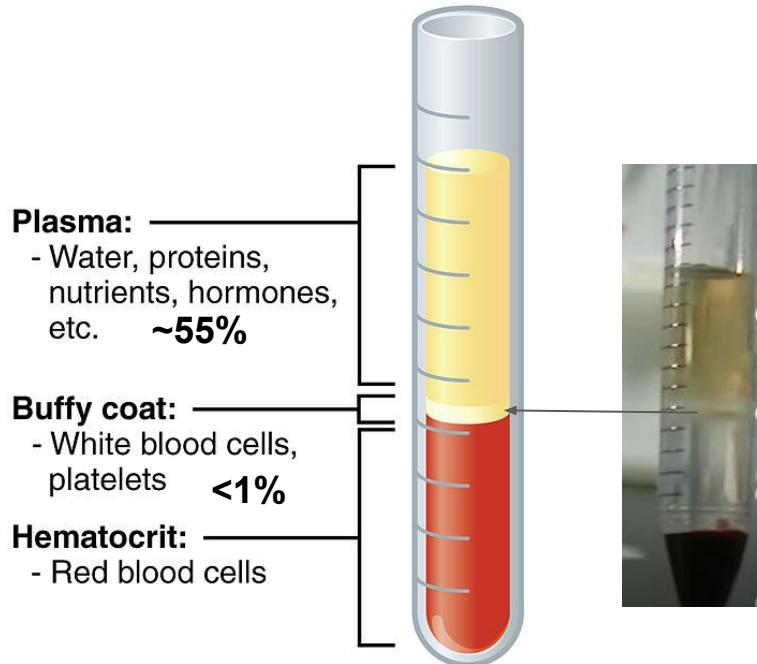
Organ: group of tissues to perform specific functions

Organ systems: group of organs and tissues



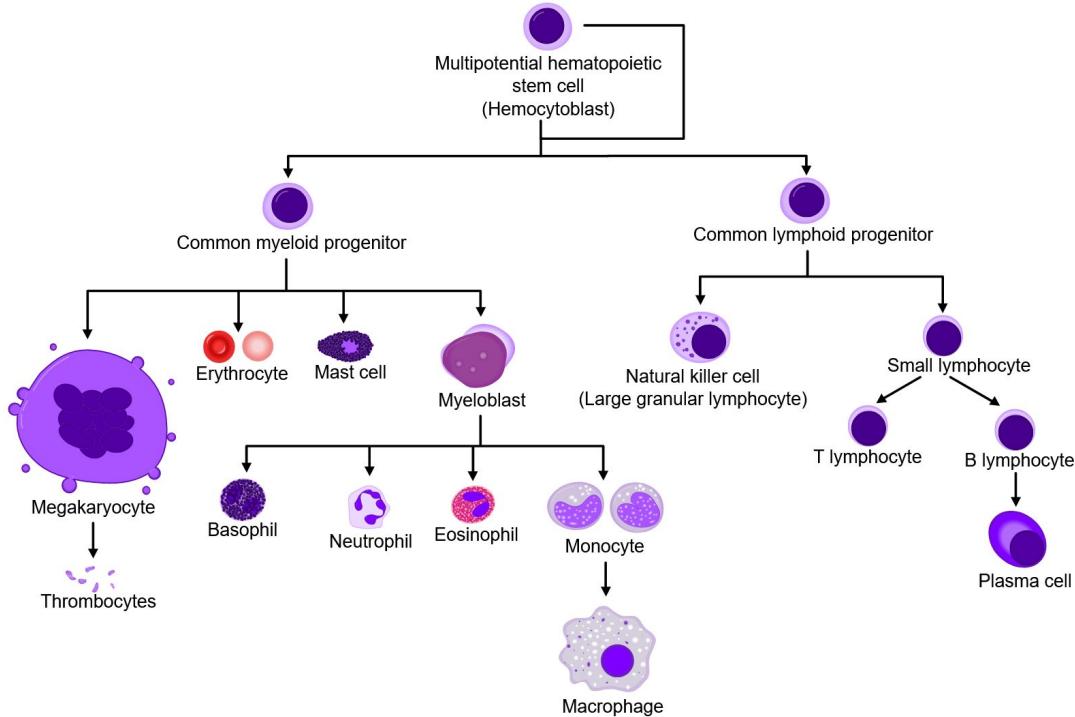


What's in a drop of blood? Ask a doctor or a biologist!



Normal Blood:

♀ 37%–47% hematocrit
 ♂ 42%–52% hematocrit

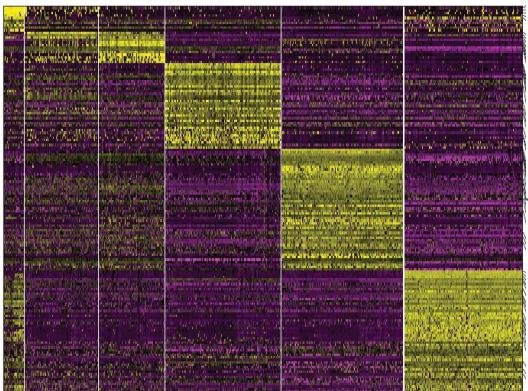


What's in a drop of blood? Count the genes!



Sequencing

Genes



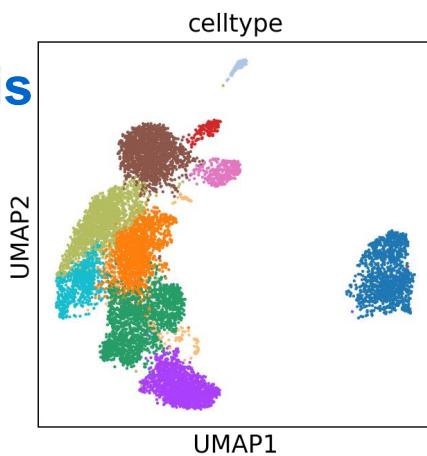
Cells

Low
Expression



High
Expression

Data
analysis



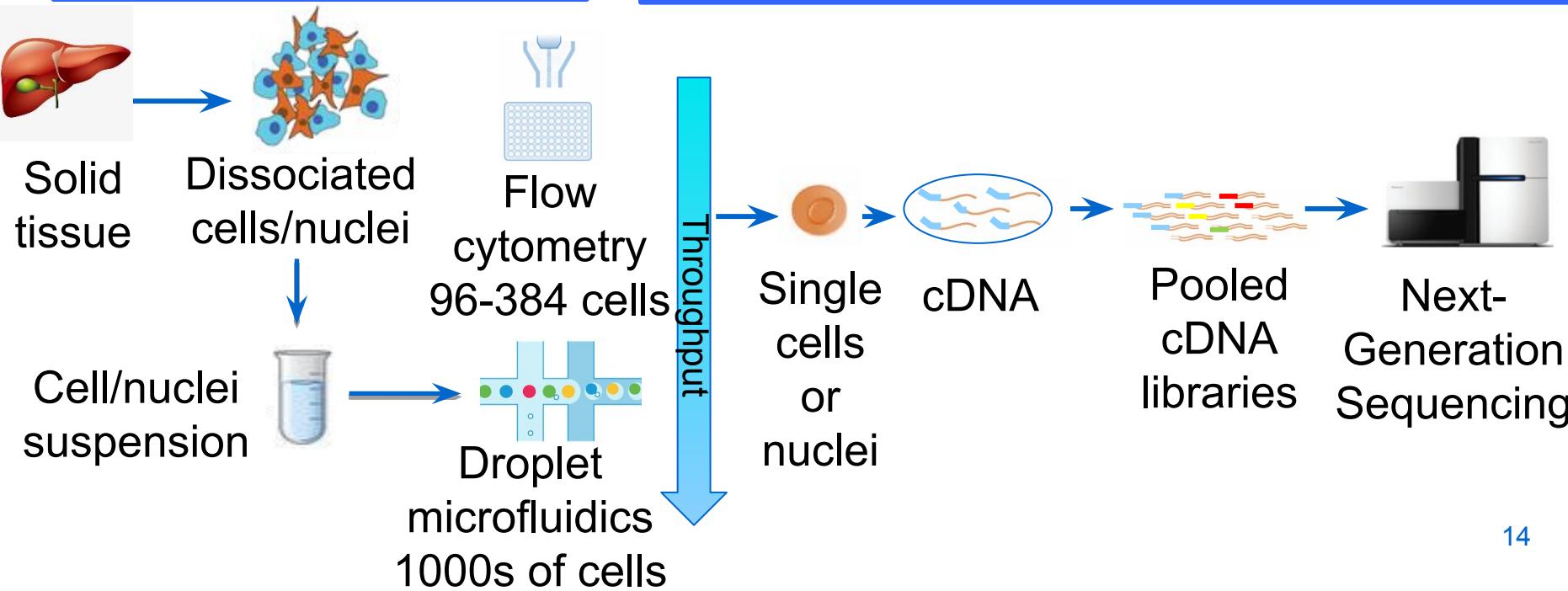
UMAP1

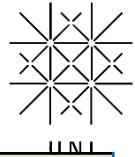
- B-cell
- CD4 T-cell
- CD8 T-cell
- DC
- NK cell
- monocyte CD14+
- monocyte CD16+
- naive CD4 T-cell
- naive CD8 T-cell
- pDC
- unknown

Single-cell sequencing (scSeq) workflow

Tissue dissociation

Single cell capture and transcriptome sequencing

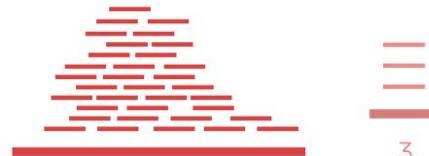




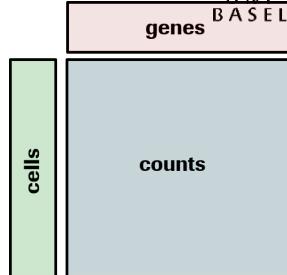
A linearized workflow of scSeq data analysis

From short reads to gene-cell matrix

Alignment Quantification

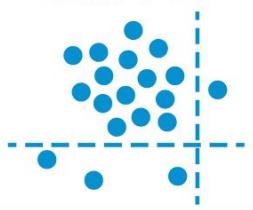


genes

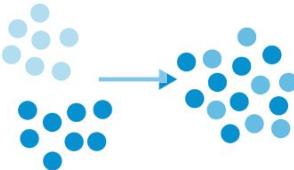


QC, filtering & normalization,
dimensionality reduction, and
clustering

Quality control



Normalisation

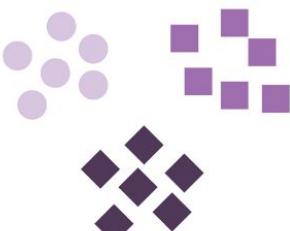


Clustering



Downstream analysis

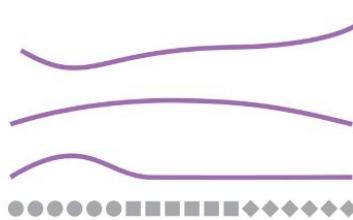
Differential expression



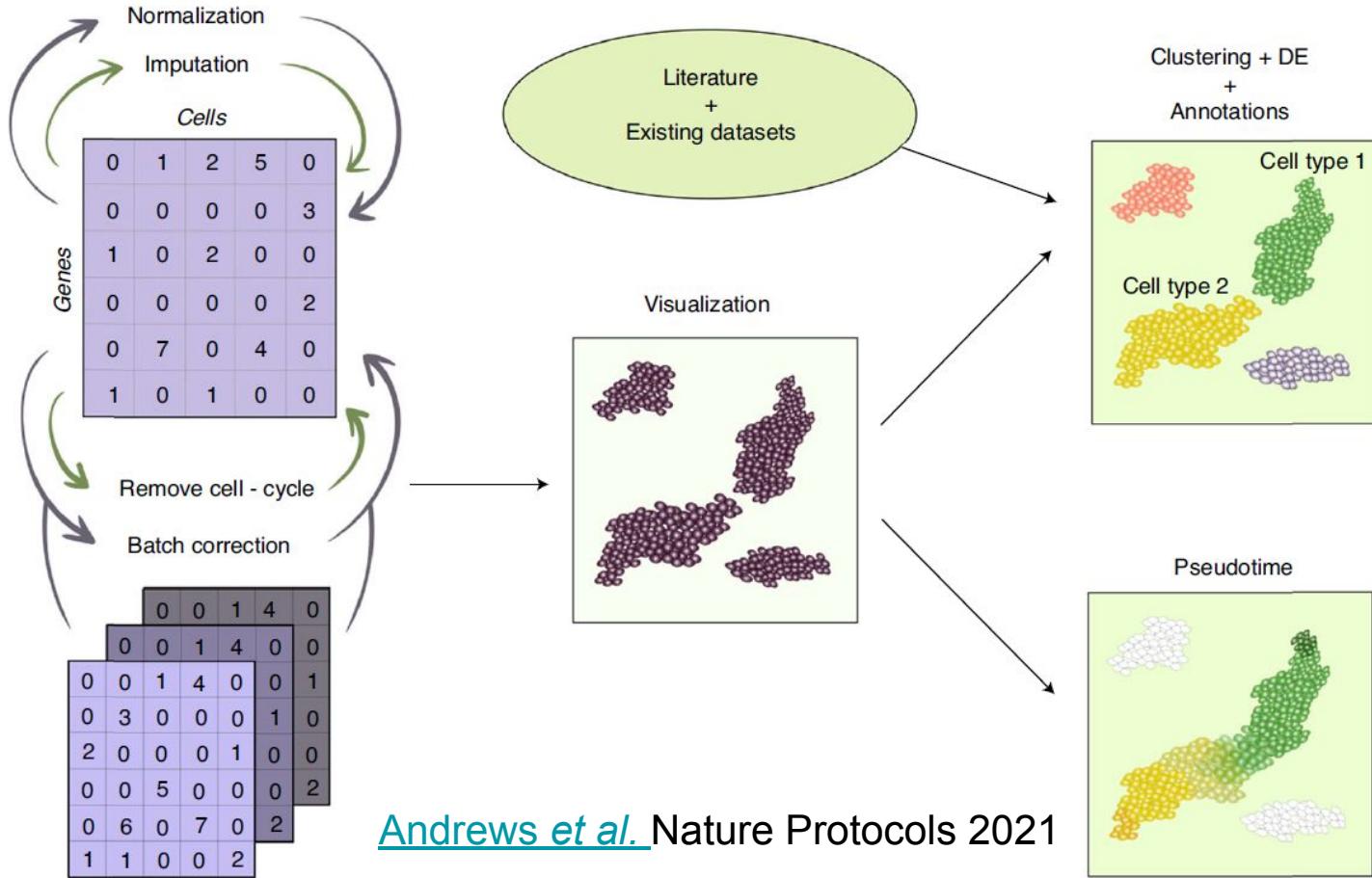
Marker genes



Expression patterns

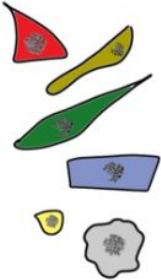
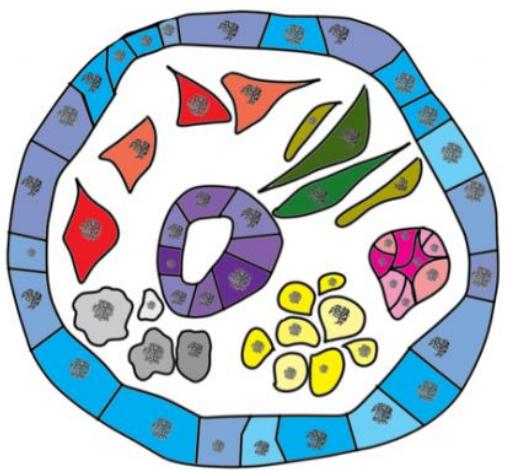


Overview of the computational workflow

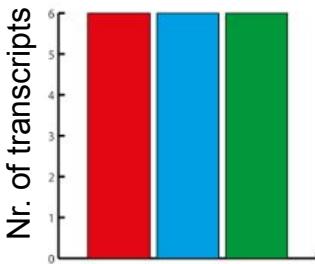


[Andrews et al. Nature Protocols 2021](#)

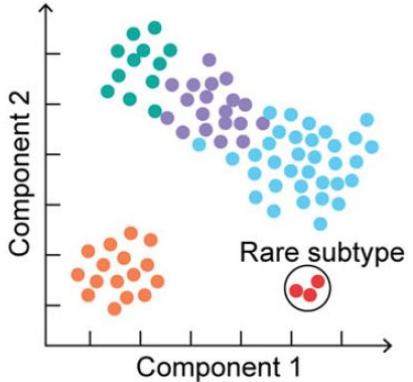
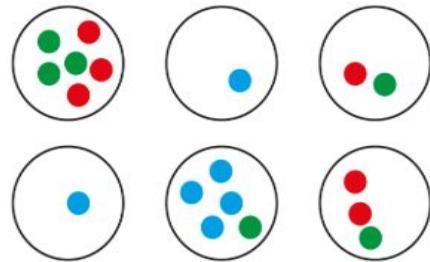
Single-cell biology benefits both disease understanding and drug discovery



Bulk analysis

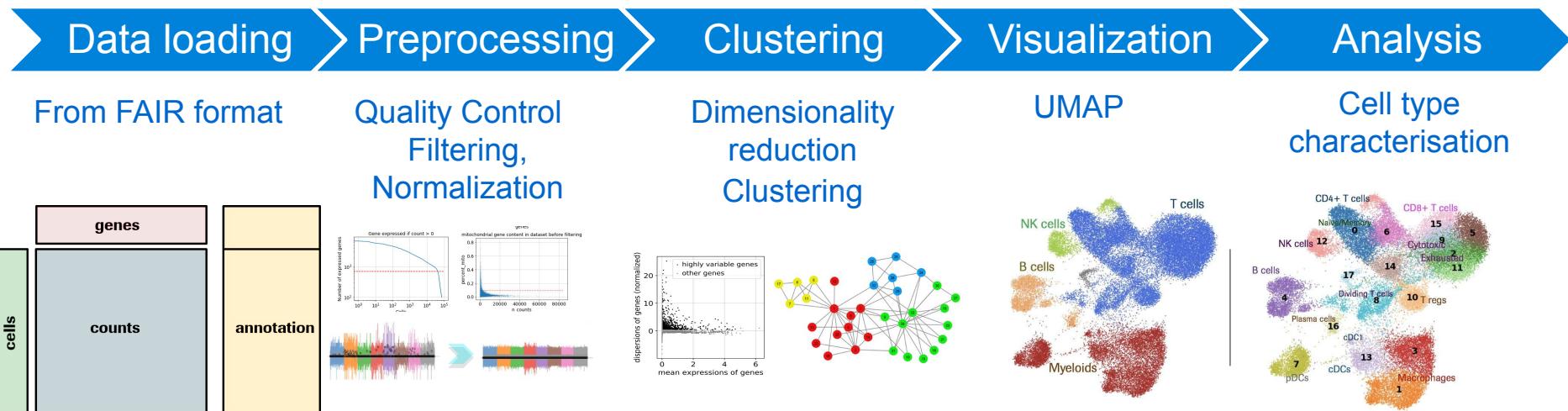


Single cell transcriptome analysis

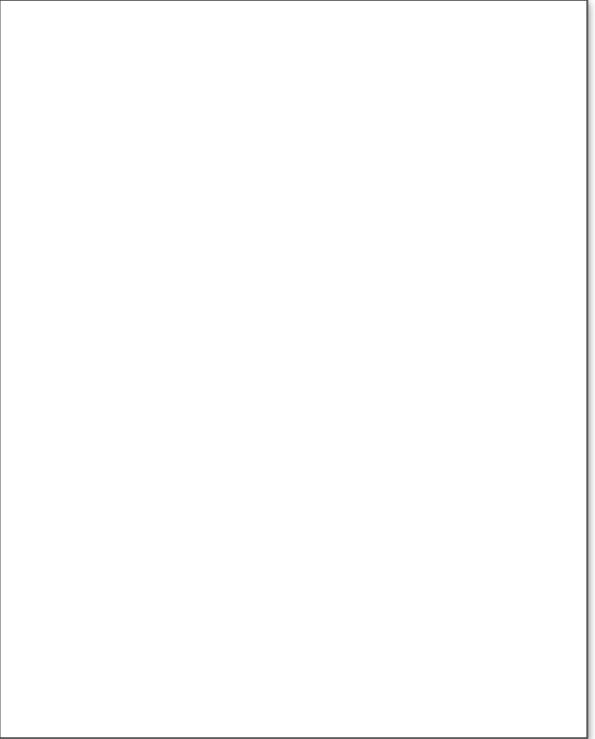


BESCA: An open-source Python package for single-cell gene expression analysis

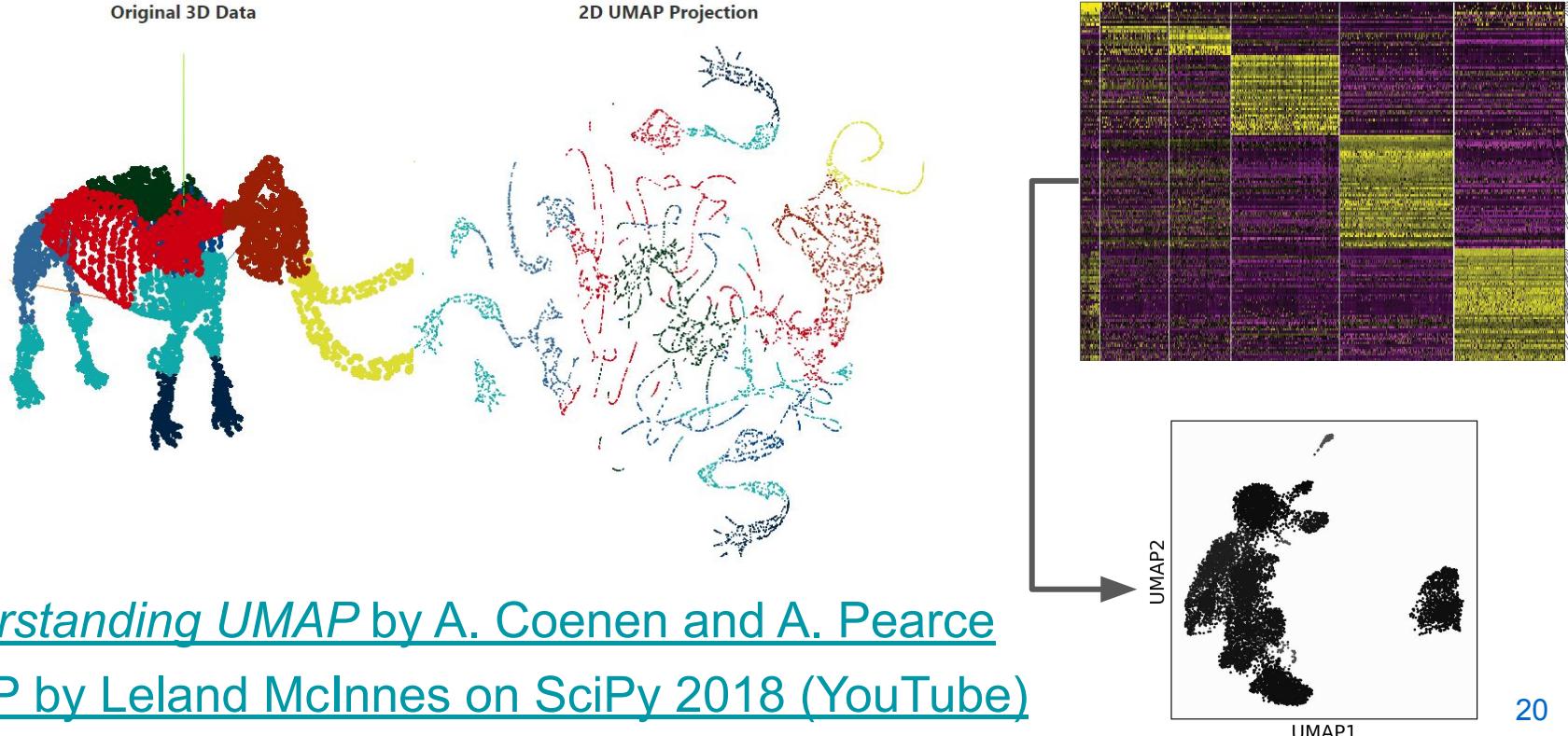
An automated standard workflow



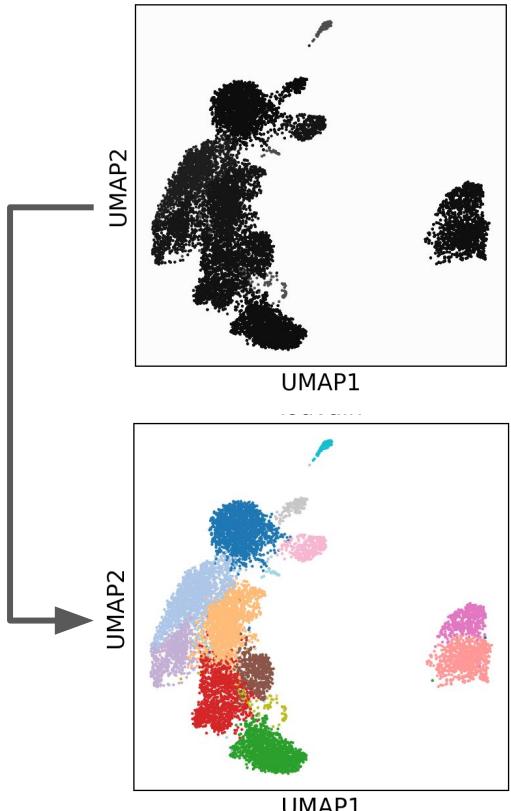
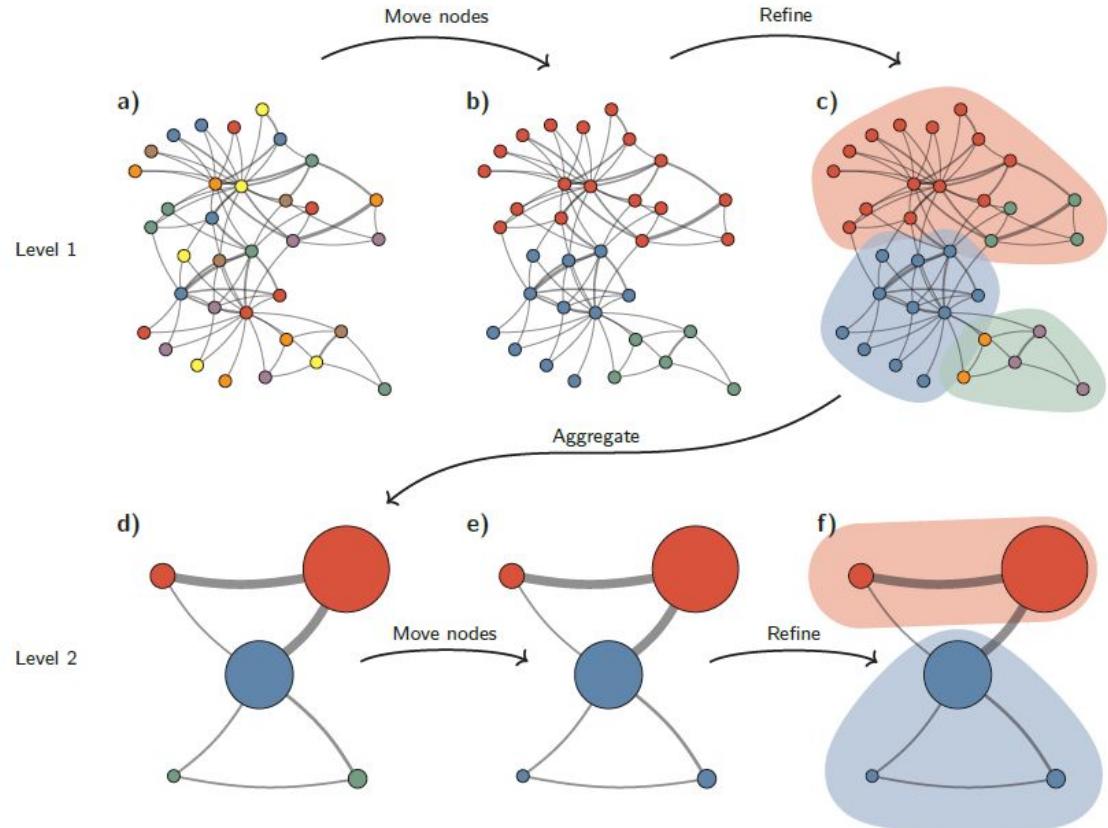
How to represent voxels with pixels?



Uniform Manifold Approximation and Projection (UMAP) for dimension reduction

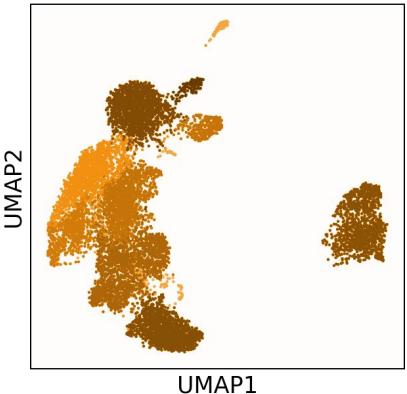


The Leiden Algorithm for Community Detection

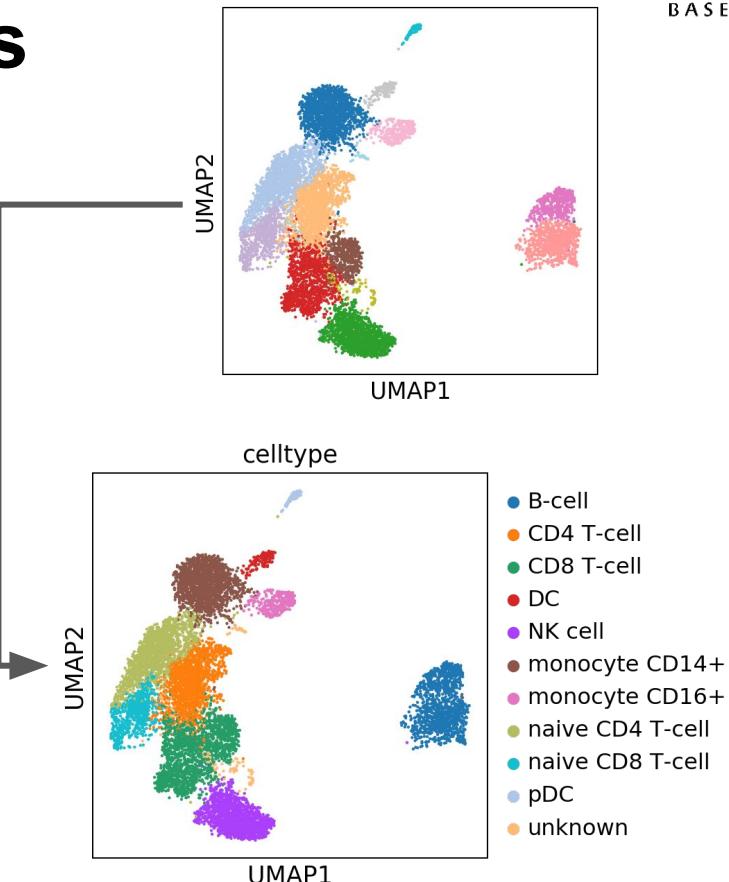


Biological knowledge and visual inspection is used to annotate cell types

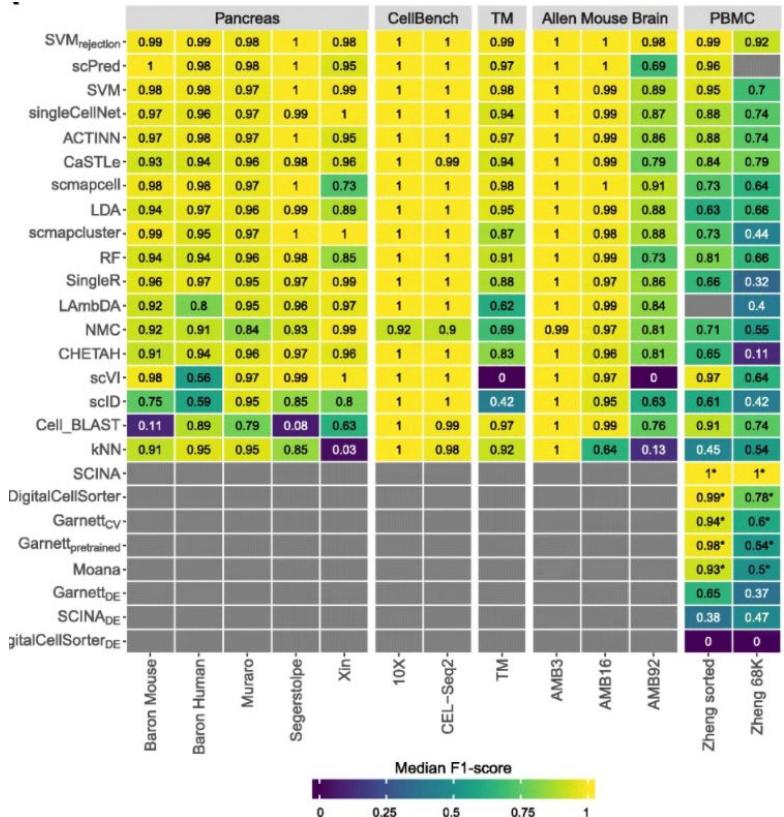
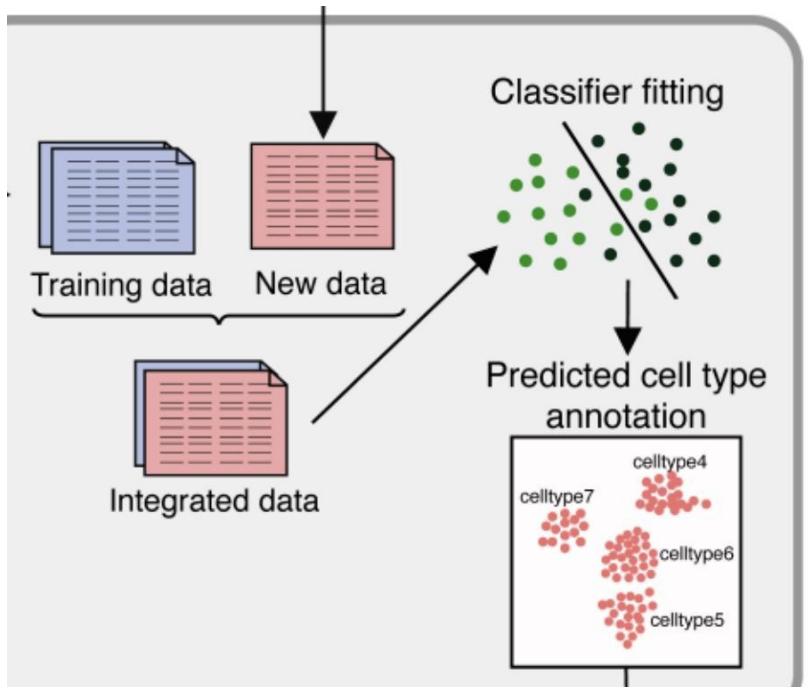
Heatmap
of gene X



lymphocyte	PTPRC							
myeloid	S100A8	S100A9	CST3					
Bcell	CD19	CD79A	MS4A1					
Tcells	CD3E	CD3G	CD3D					
CD4	CD4							
CD8	CD8A	CD8B						
NKcell	NKG7	GNLY	NCAM1					
monocyte	CST3	CSF1R	ITGAM	CD14	FCGR3A	FCGR3B		
macrophage	CD14	IL1B	LYZ	CD163	ITGAX	CD68	CSF1R	FCGR3A



Cell type annotation with machine learning

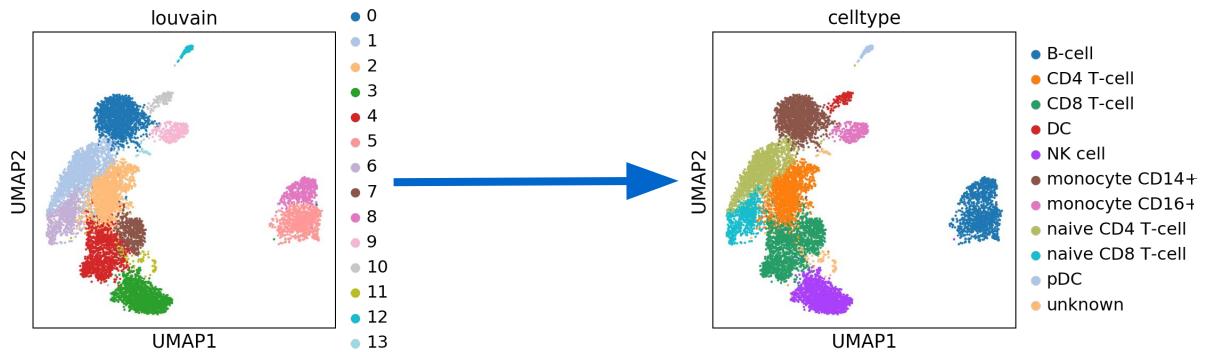


An intern project: Cell type annotation

From unsupervised clustering and cluster based annotation



Luis Wyss
RAAN intern 2019



	Gene 1	Gene 2	Gene 3	Gene 4	Gene 5	Label
Training Cell 1	10	50	0	12	4	Celltype A
Training Cell 2	8	45	78	3	23	Celltype B
Training Cell 3	14	55	78	65	55	Celltype B
Training Cell 4	78	12	13	9	58	Celltype A
Training Cell 5	45	23	65	98	11	Celltype C

To supervised annotation at single-cell level:

	Gene 1	Gene 2	Gene 3	Gene 4	Gene 5
Cell 1	45	45	8	56	3
Cell 2	65	120	78	45	12
Cell 3	79	12	34	65	88
Cell 4	7	59	32	47	62

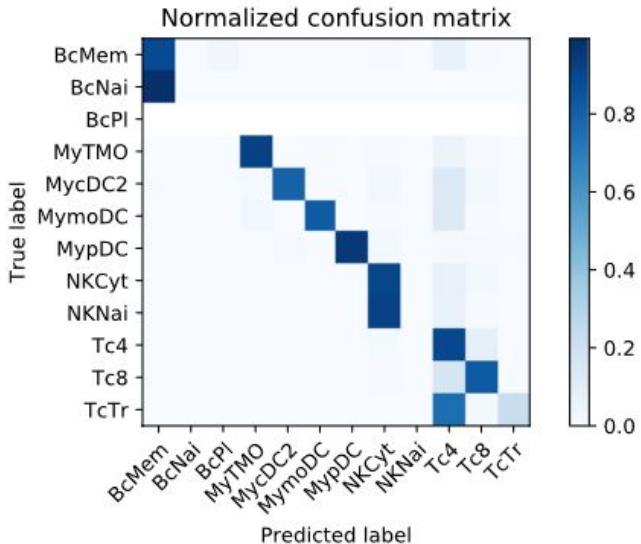
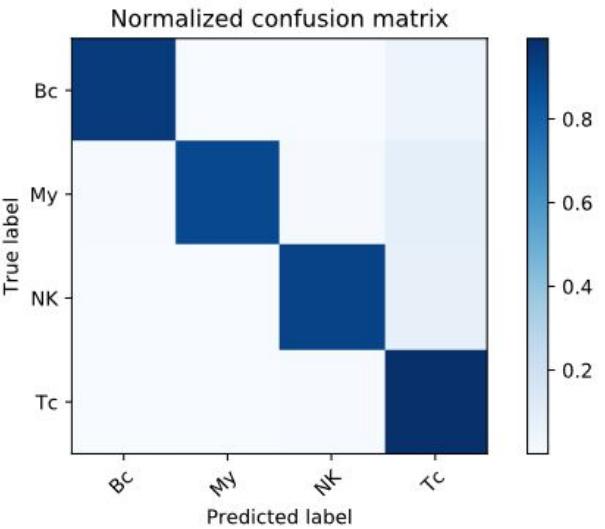
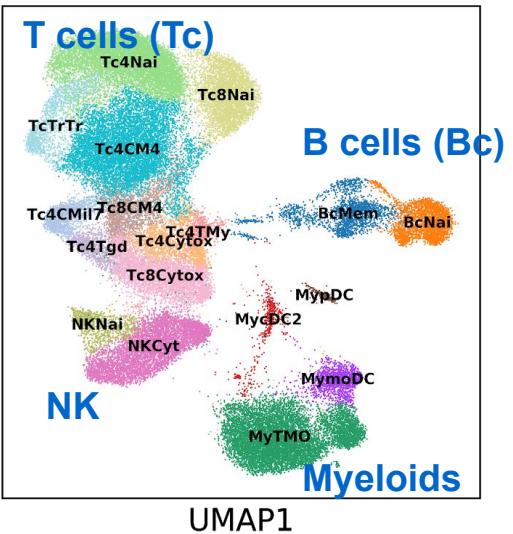


	Gene 1	Gene 2	Gene 3	Gene 4	Gene 5	Prediction
Cell 1	45	45	8	56	3	Celltype A
Cell 2	65	120	78	45	12	Celltype B
Cell 3	79	12	34	65	88	Celltype C
Cell 4	7	59	32	47	62	Celltype B



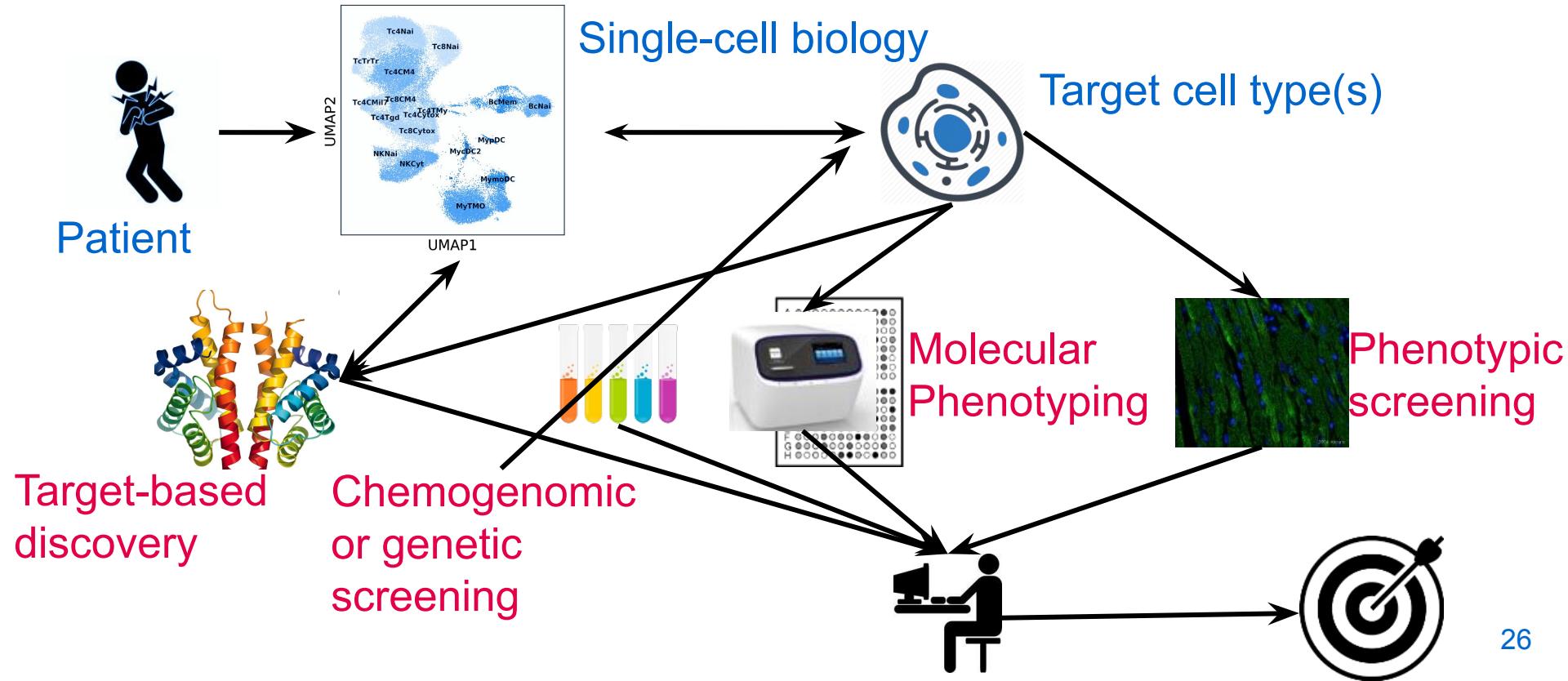
Advantages: (1) automation, (2) annotation independent from clustering, and (3) we can estimate the confidence of prediction

A PBMC example of cell type annotation



- Broad level cell types, including B cells (Bc), Myeloid (My), NK cells (NK) and T cells (Tc), are successfully predicted.
- Missing and highly similar cell types cause challenges with increased granularity. Essential: reference data quality and knowledge of cell types. 25

Computational biologists work with experimentalists to empower drug discovery



We are living ecosystems

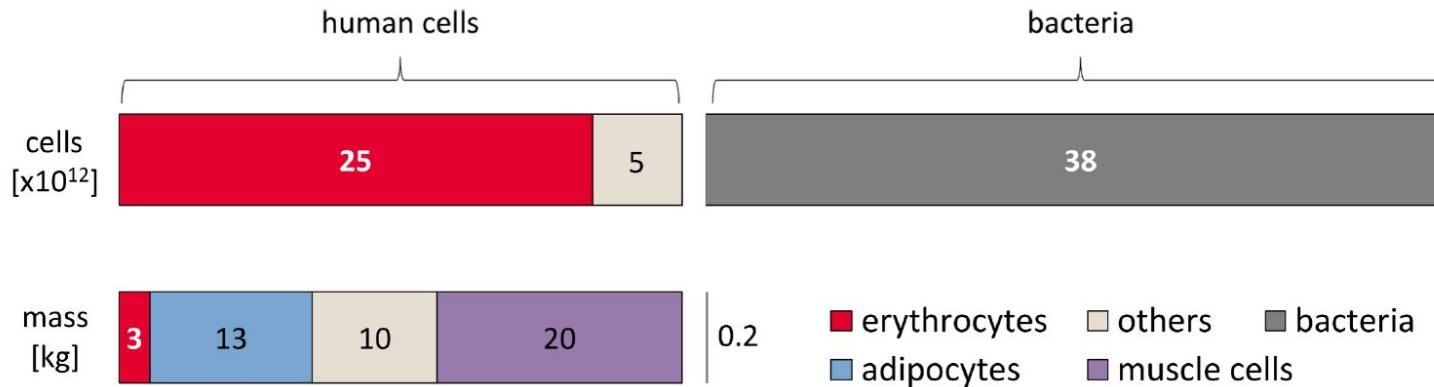
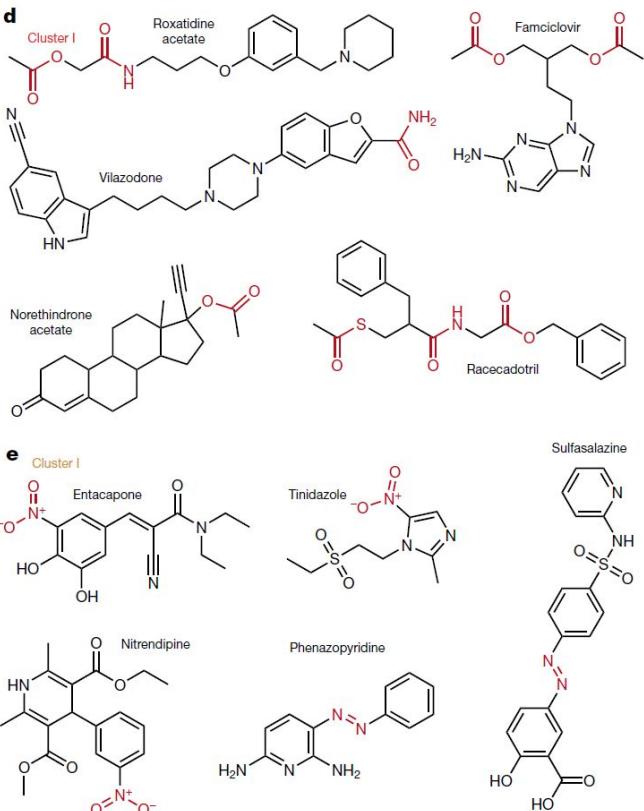
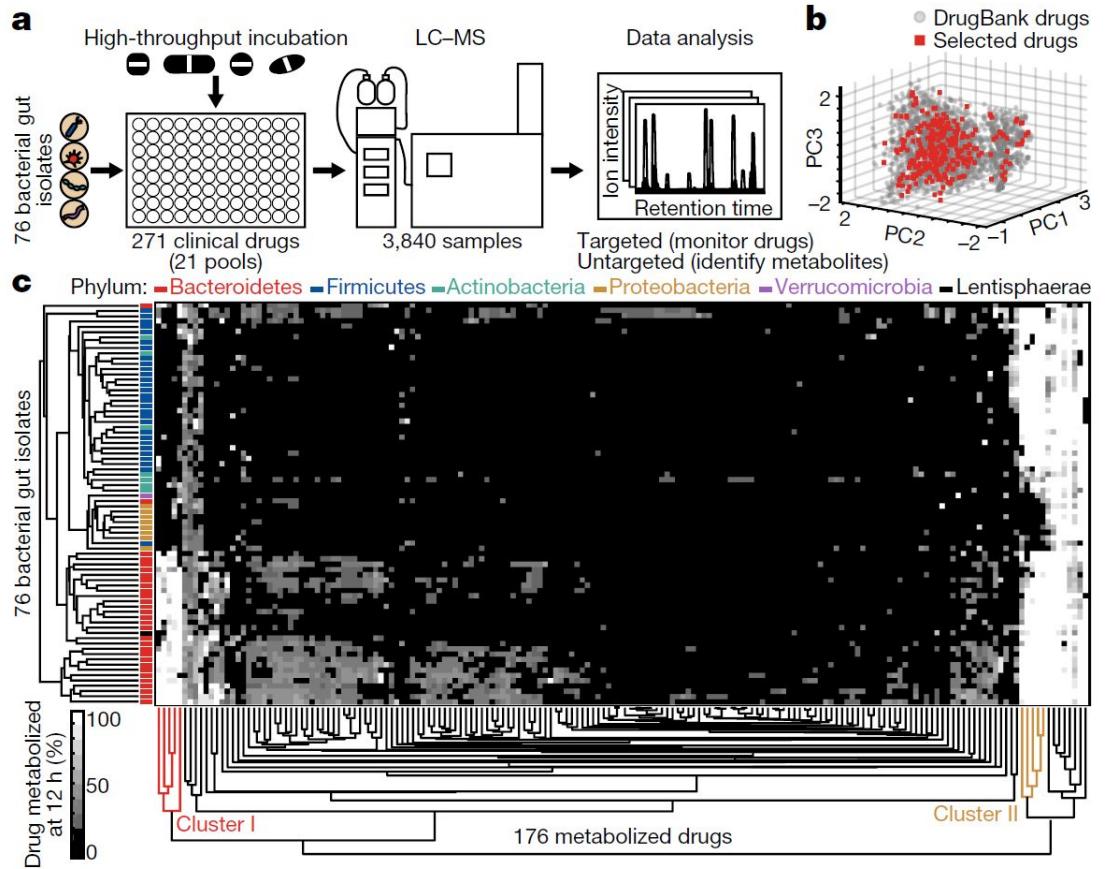


Table 3. B/H ratio for different population. See Table B in [S1 Appendix](#) for full references.

population segment	body weight [kg]	age [y]	blood volume [L]	RBC count $[10^{12}/L]$	colon content [g]	bac. conc. $[10^{11}/g \text{ wet}]^{(1)}$	total human cells $[10^{12}]^{(2)}$	total bacteria $[10^{12}]$	B:H
ref. man	70	20–30	4.9	5.0	420	0.92	30	38	1.3
ref. woman	63		3.9	4.5	480	0.92	21	44	2.2
young infant	4.4	4 weeks	0.4	3.8	48	0.92	1.9	4.4	2.3
infant	9.6	1	0.8	4.5	80	0.92	4	7	1.7
elder	70	66	3.8 ⁽³⁾	4.8	420	0.92	22	38	1.8
obese	140		6.7	5.0 ⁽⁴⁾	610 ⁽⁵⁾	0.92	40	56	1.4

Gut microbiome can metabolize drugs differently



Conclusions

- Single-cell biology can identify rare cell populations associated with diseases, and investigate cell-type-specific perturbations caused by drug candidates.
- Algorithms for dimensionality reduction, clustering, and semi-automated cell type annotation allow us interpret and integrate single-cell datasets.

Offline activities of Module IV (optional)

Perform your own single-cell data analysis to get first-hand experience working with high-dimensional biological data.

- If you are new to the topic, please use [the PBMC tutorial of Scanpy \(python\)](#) or [the PBMC tutorial of Seurat \(R\)](#).
- If you have experience with such data already, checkout [the NBIS workshop on single-cell sequencing data analysis](#) to cover advanced topics such as spatial transcriptomics and trajectory inference.

Single-cell biology is important in drug discovery

Disease understanding:

disease-specific cell types
and states



Target identification:

expression pattern in
health and disease across
cell types



Biomarker and patient stratification:

which genes should we measure
in which cell type(s)?



MoA and safety

modelling: perturbation effect at single-cell level



Outline of Lecture 10

- We predict efficacy and safety profiles of drugs by studying the mechanism and mode of action (MoA).
- Molecular modelling and (single-cell) RNA sequencing analysis are essential tools for understanding MoA of nucleotide-based modalities.
- Molecular modelling and proteomics based on mass spectrometry (MS) are essential tools for understanding MoA of small molecules and antibodies.

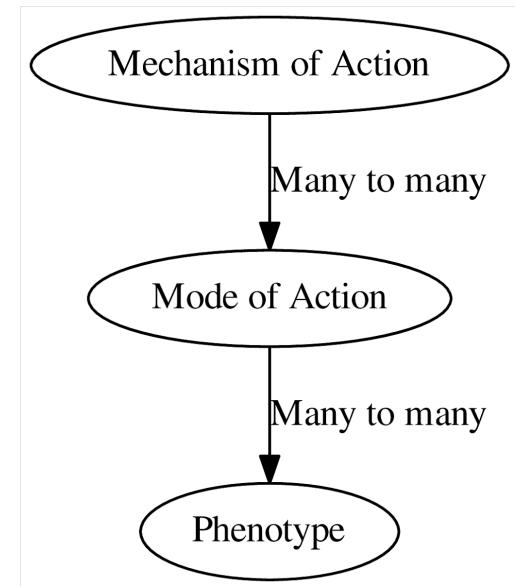
Questions & Answers for the Guest Lectures

- Concerning Tony Kam-Thong's talk (about dynamic systems and time-series data analysis), (1) I wonder how do concepts fit into the grand scheme of drug discovery? (2) Whether a pharmaceutical company encourages employees to focus on a single topic of research, or to gain and contribute knowledge in many different projects?
- There are many scRNA library methods (https://teichlab.github.io/scg_lib_structs/). How do I know which method is popular, efficient, or industrial de facto standard?
- We discussed human biology as a Complex Adaptive System (CAS). I would expect companies apply this kind of simulation like agent-based modeling. If you have any research related, could you introduce them?

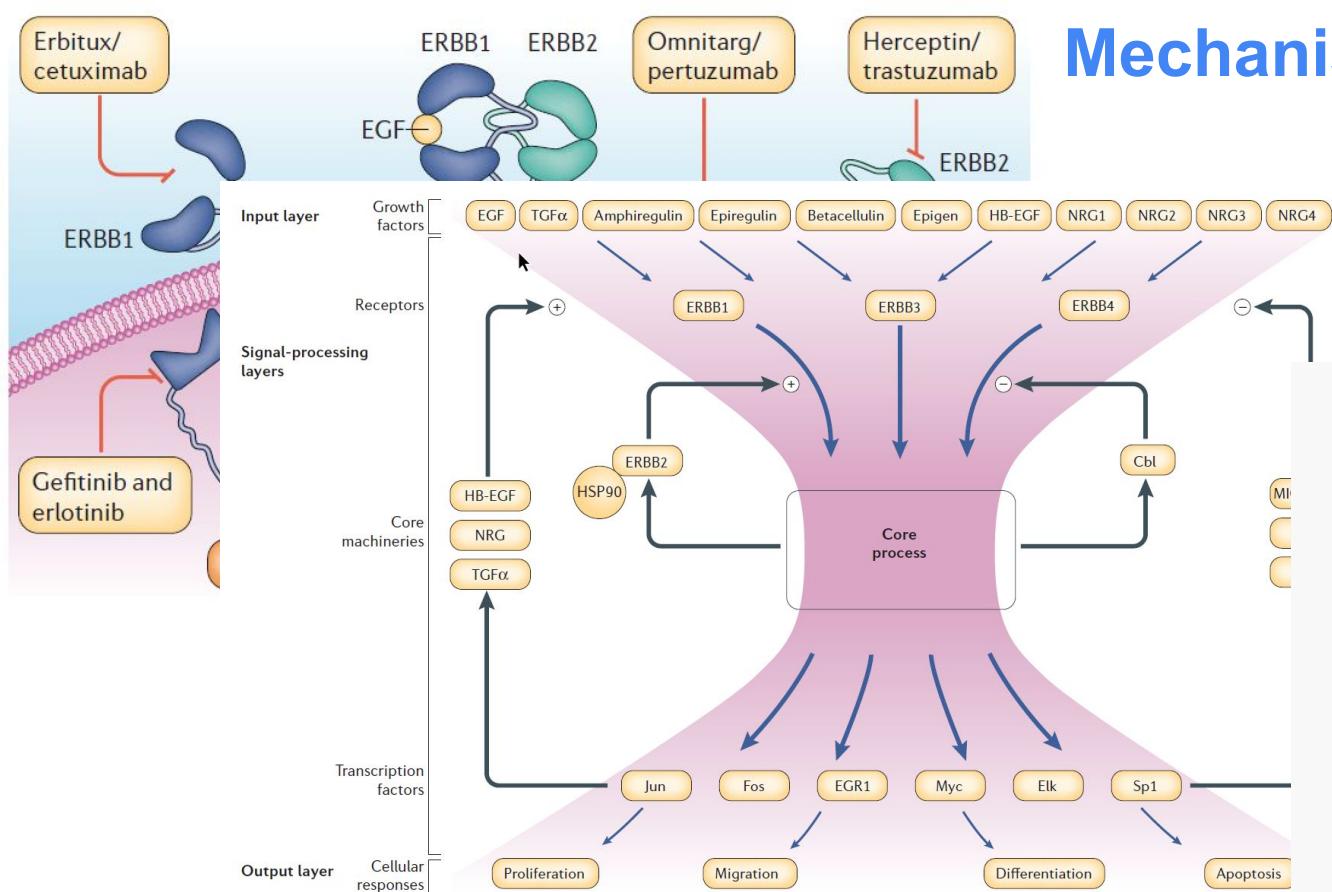
Mechanism of Action at the molecular level and ***Mode of Action*** at cellular and system levels

Mechanism of Action: The biochemical interactions through which a drug exerts its pharmacology and toxicity.

Mode of Action: Functional or anatomical changes of cells, or organ and tissue systems resulting from the exposure to a drug.

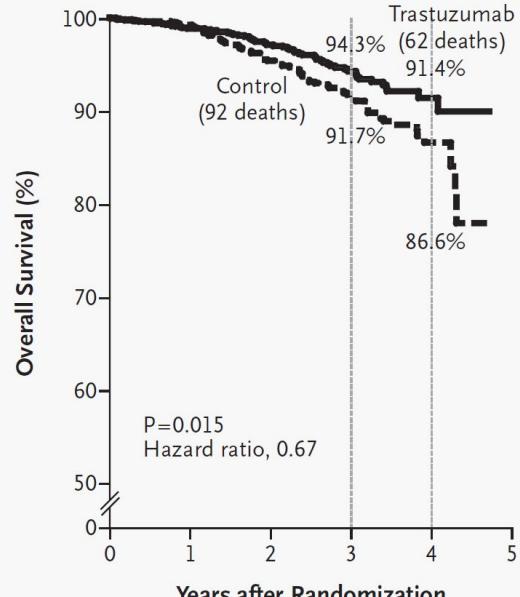


Mechanism of Action



Mode of Action

Phenotype

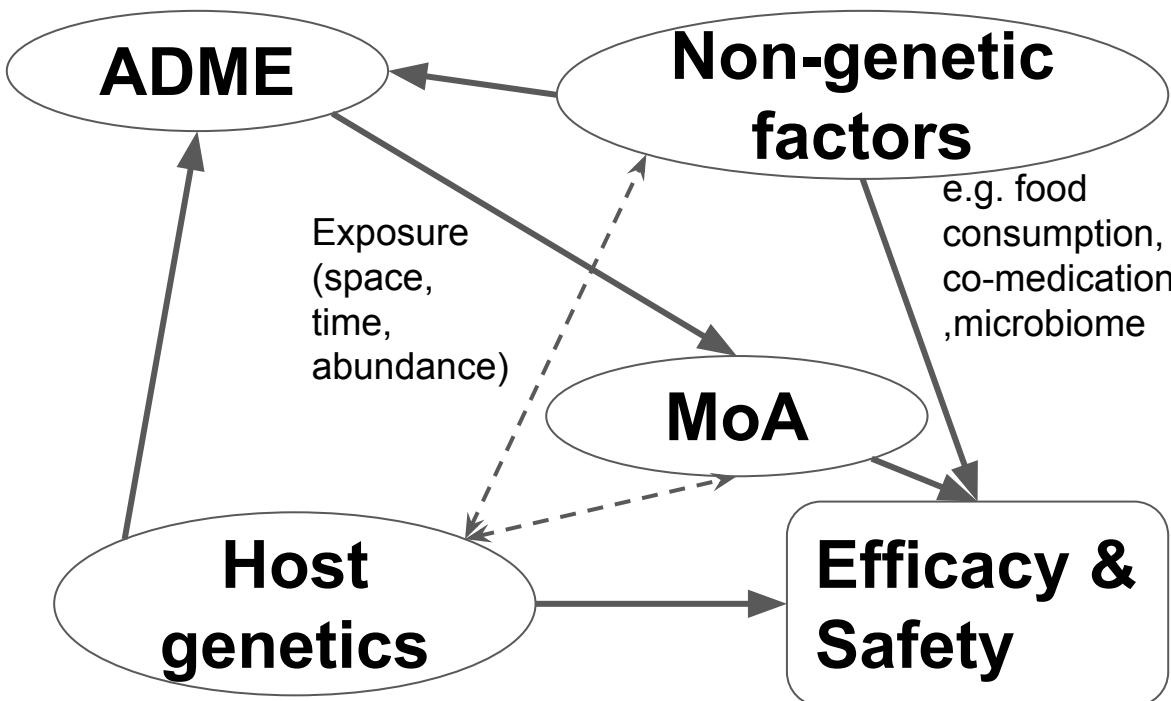


Mechanism and Mode of Action determine phenotypes

No. at Risk	3351	2441	1571	908	165	0
Control	1679	1200	766	448	83	0
Trastuzumab	1672	1241	805	460	82	0

Host genetics, non-genetic factors, MoA, and ADME together influence efficacy and safety

In this lecture, MoA refers to both Mechanism and Mode of action, because we need to understand **both** to make a good drug.



Four approaches for MoA understanding

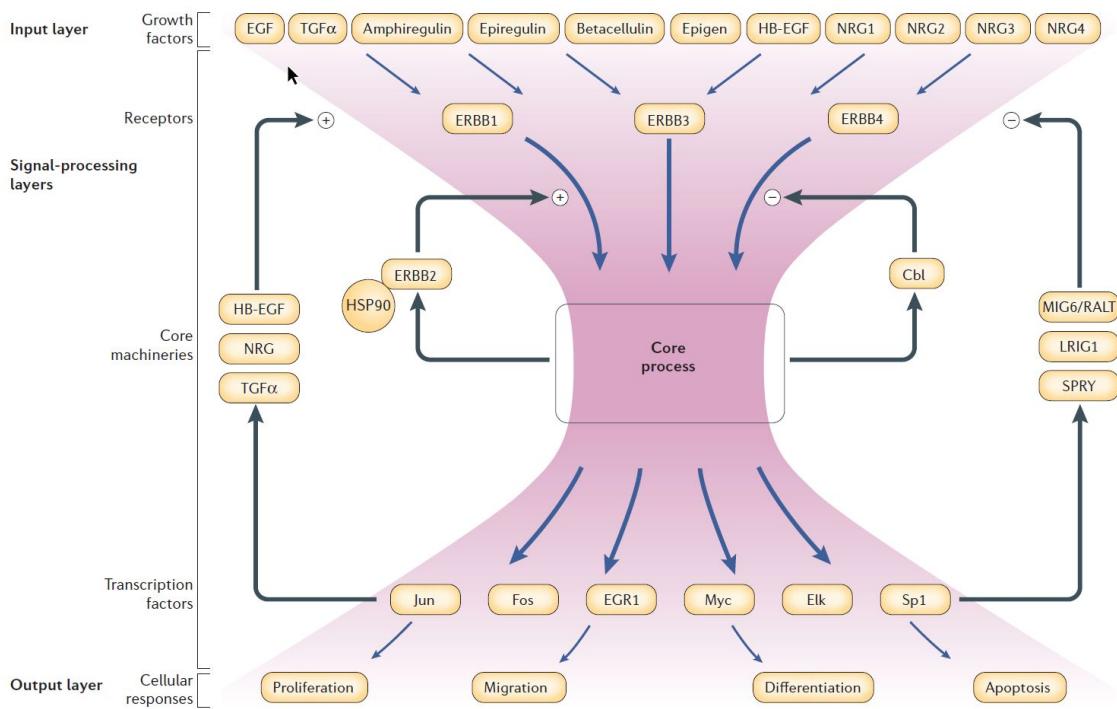
- Imaging-based methods
- Direct biochemical methods
- **Computer-assisted inference methods**, e.g. sequence analysis and molecular modelling
- **Omics based methods**, e.g. transcriptomics (RNA-seq) and **proteomics (mass spectrometry)**

} Covered before

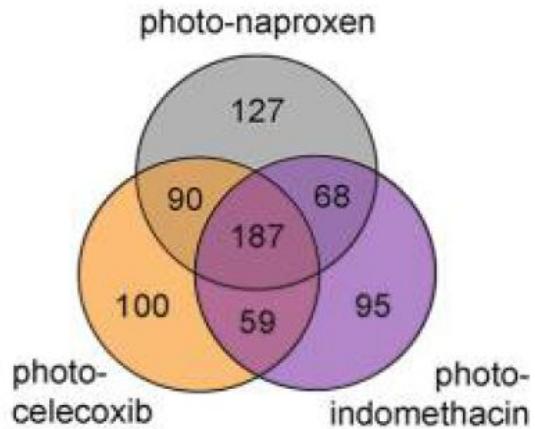
} Focus today

Challenge #1: Many Causes, Same Effect

Different
Mechanisms of
Action *may or may
not* lead to the
same Mode of
Action.



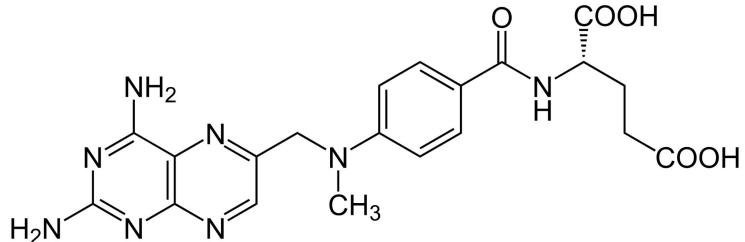
Challenge #2: Multiple MoAs are possible



Non-steroid anti-inflammatory drugs (NSAIDs) are thought to work by inhibiting proteins Cox-1 and Cox-2.

A recent study (Gao *et al.* 2018) reports that they bind to a surprisingly high number of proteins in cells.

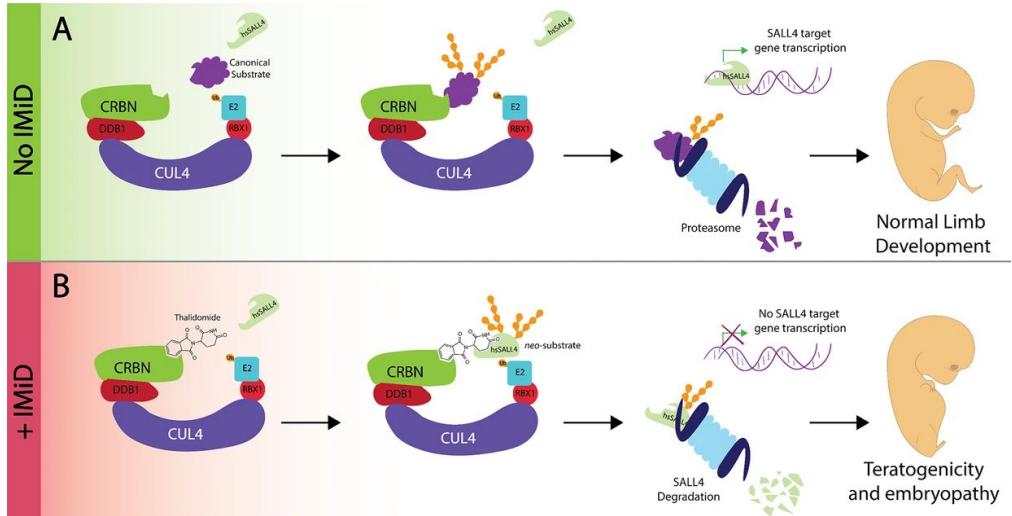
Methotrexate



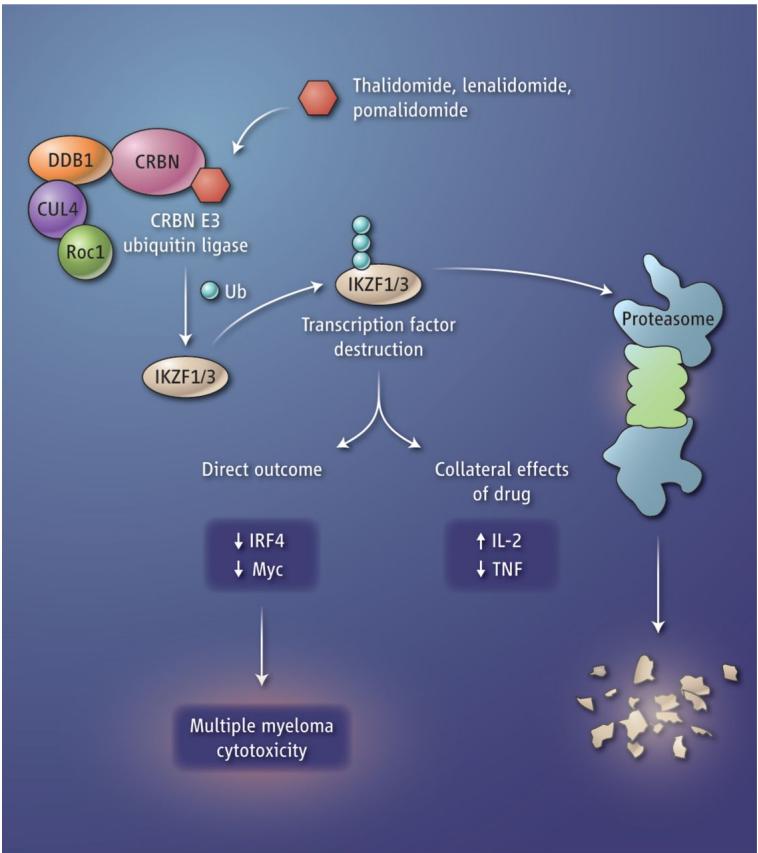
[As chemotherapy agent] Inhibiting dihydrofolate reductase (DHFR) and consequently DNA synthesis.

[As immunosuppressant] Multiple mechanisms, e.g. (1) inhibiting purine metabolism, (2) inhibiting methyltransferase, and (3) inhibiting IL-1 β binding to its receptor.

Challenge #2: Multiple MoAs are possible

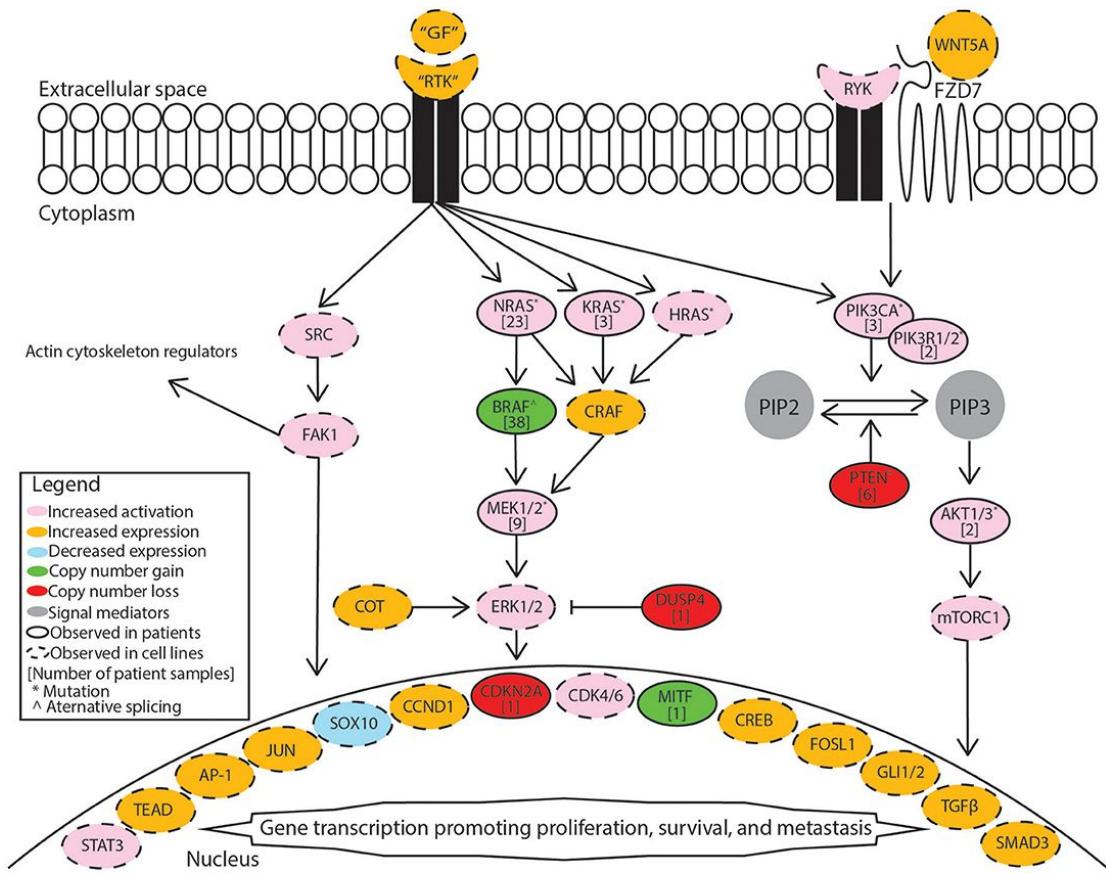


Thalidomide employs the same ubiquitination system to degrade different targets in teratogenicity (left) and in leukemia (right).



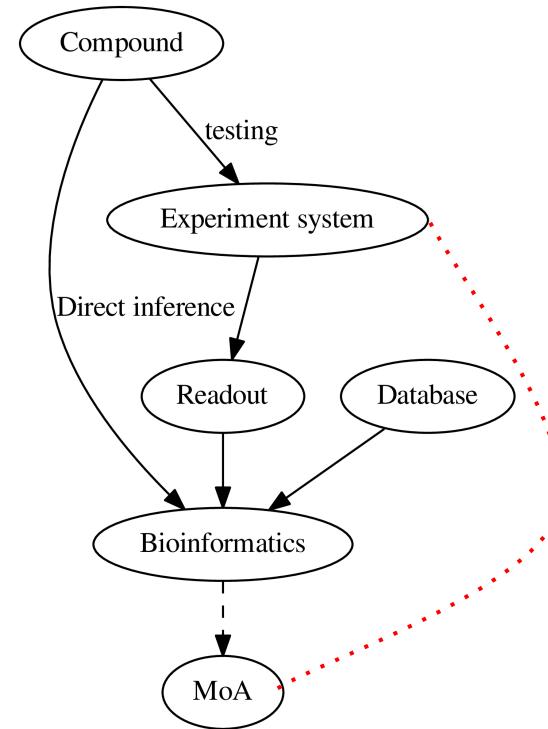
Challenge #3: Genetics may affect MoA

- Genetics may predispose individuals to different responses;
- Feedback loop and mutations may lead to drug resistance.



Computational biology contributes to MoA understanding by data analysis and integration

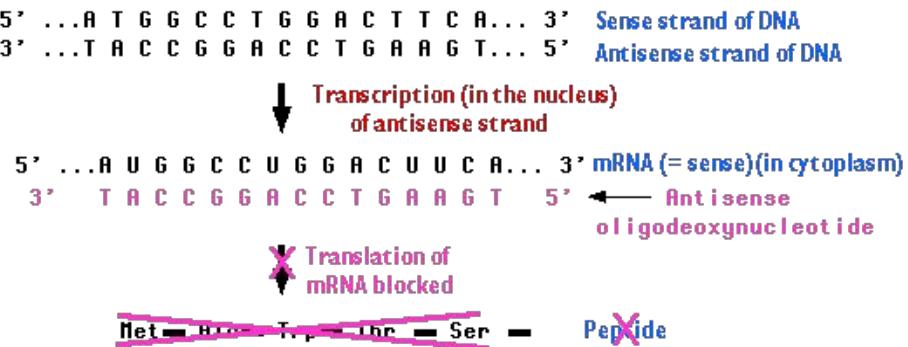
- MoA can be inferred either with the information of the compound alone, or with the data generated *in vitro* or *in vivo*.
- Prior knowledge encoded in databases is often of great help.
- The process is always iterative with hypothesis-testing cycles.
- Below we illustrate modality-specific approaches



Understanding MoA of antisense oligonucleotides

Sequence-dependent binding of oligonucleotides induces both on- and off-target effects

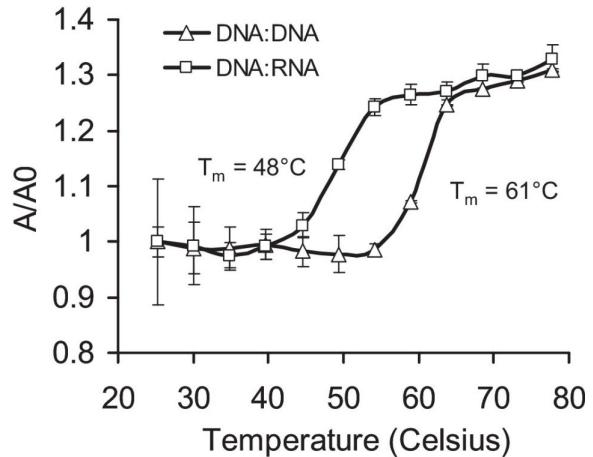
- Antisense Oligonucleotides (ASOs) work by binding to mRNA transcripts in a **sequence-dependent** way.
- ASO-mRNA binding is a chemical reaction with a spectrum of affinities. For simplification (!), we often use the following classification:
 - **On-target**, usually of one mRNA species.
 - **Off-targets** potentially of many undesired mRNA species.
 - **Non-targets**, hardly bound by the ASO, though they can be potentially regulated by secondary effects.



<i>Human mRNAs</i>	
<i>My silver-bullet oligo (3'-5')</i> TACCGGACCTGAAGT	AUGGCCUGGACUUCA AUGGCCUGGUUUCA AUGGCCUGCUUUCA AUGGCCACCACUUCA ...
	On target
	Off target
	Off target
	Non target
	UACGUCGUAGUCUUC
	Non target

The binding affinity between RNA and ASO can be measured by the melting temperature T_m

- Binding affinity between RNA and ASOs can be measured by the duplex melting temperature (T_m), the temperature at which half of the ASOs are duplexed with RNA.
- The higher is the T_m , the stronger is the binding, when other conditions are constant.



Name	Target	Sequence (5' to 3') ^a	Length (nt)	T_m (°C)
T1	<i>Tradd</i>	GctcatactcgtaggcCA	18	66.8
T2	<i>Tradd</i>	GCtgcataactcgtaggcCA	18	69.7
T3	<i>Tradd</i>	GCtgcataactcgtagggCCA	18	72.1
T4	<i>Tradd</i>	GCTcataactcgtaggcCA	18	73.3
T5	<i>Tradd</i>	GCTcataactcgtagggCCA	18	76.3

Question: when other conditions are constant, which ASO binds strongest to the target gene *Tradd*?

Predicting melting temperature (i.e. binding affinity) of ASO-mRNA pairs with *free energy*

- It is possible to predict T_m , using the nucleotide sequences and the principles of **nucleic acid thermodynamics**.
- The melting temperature is correlated with the free energy (ΔG°), which can be predicted by dynamic-programming algorithms.
- **The more negative the free energy is** (i.e. the larger the absolute value is), the higher is T_m , namely the **ASO-mRNA pair is more likely to be stable**.

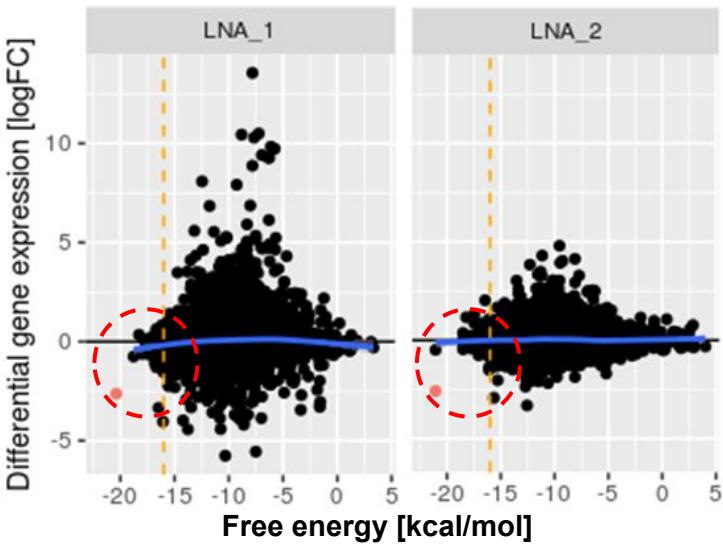
<i>Human mRNAs</i>	<i>Free Energy (kcal/mol)</i>
AUGGCCUGGACUUCA	-32.8
AUGGCCUGGUUUCA	-28.5
AUGGCCUGCUUUCA	-23.7
AUGGCCACCACUUCA	-20.2
...	
UACGUCGUAGUCUUC	-9.8

My silver-bullet oligo (5'-3')
TGAAGTCCAGGCCAT

Question: Other conditions held constant, which mRNA has the highest predicted T_m given the data?

Transcriptomics profiling allows simultaneous investigation of on- and off-target effects

- RNA-sequencing is able to quantify both on- and off-target effects of ASOs by measuring gene expression changes.
- Differential gene expression analysis can be used together with ASO-mRNA binding-affinity prediction to reveal off-target potentials of the tested ASOs.
- At the same time, RNA-sequencing can review pathway- and network-level changes induced by ASOs, to inform both efficacy and safety studies.

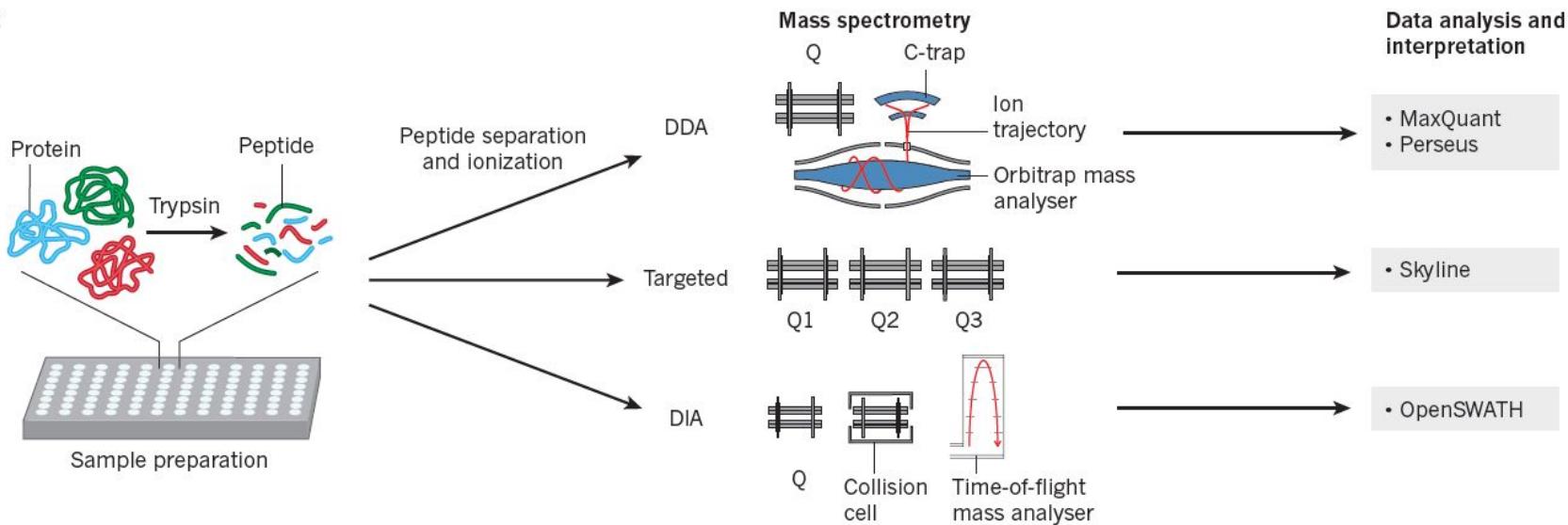


A declining trend at the left end (red dashed circle) is a warning sign: mRNAs that are predicted bound to the ASO are down-regulated, revealing potential off-target effects.

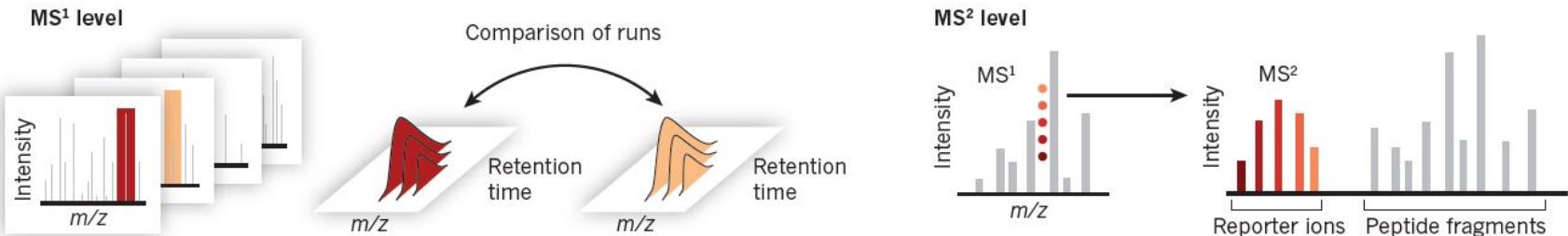
Understanding MoA of small molecules and antibodies with proteomics

Characterizing proteomes with mass spectrometry

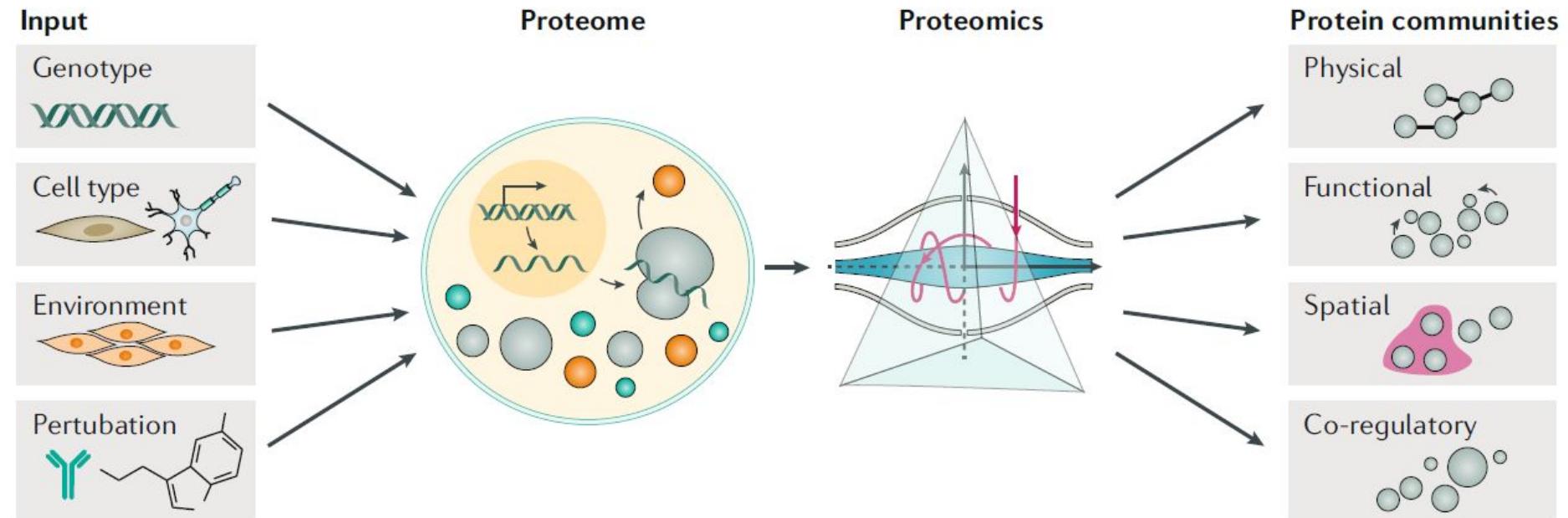
a



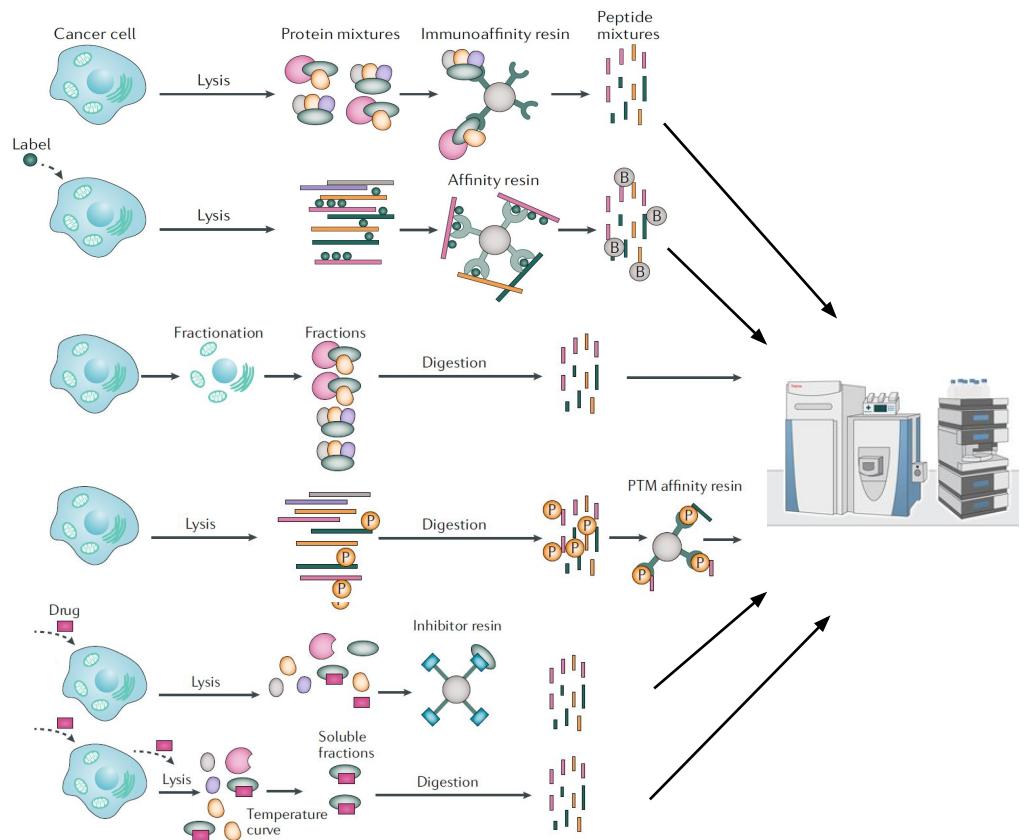
b Peptide quantification



Proteomics enables the elucidation of protein relations in the protein communities



Proteomics approaches for drug discovery



Experimental approach

Affinity purification

Applications in drug discovery

Identification of drug-dependent **PPIs** and **protein-drug** interactions; characterization of **protein complex stoichiometry**

Proximity labelling

Characterization of **unbounded cellular compartments**, and **transient PPIs**

Organelle proteome profiling

Characterization of protein communities of all major **organelles** in one dataset, drug-induced **translocation**, and **secreted signaling factors**

PTM profiling

Characterization of **time- and dose-dependent signaling events** mediated by **PTM**

Chemoaffinity enrichment

Potential **drug targets** and **off-targets**

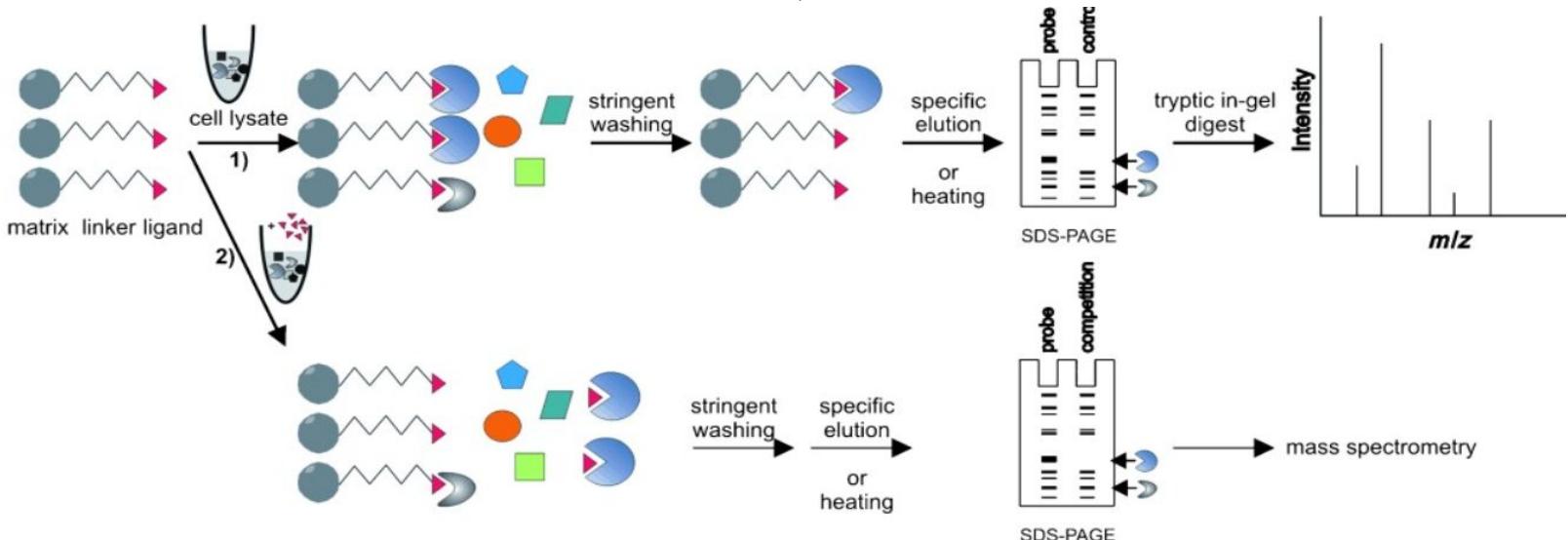
Thermal proteome profiling

Potential **drug targets** and **off-targets**

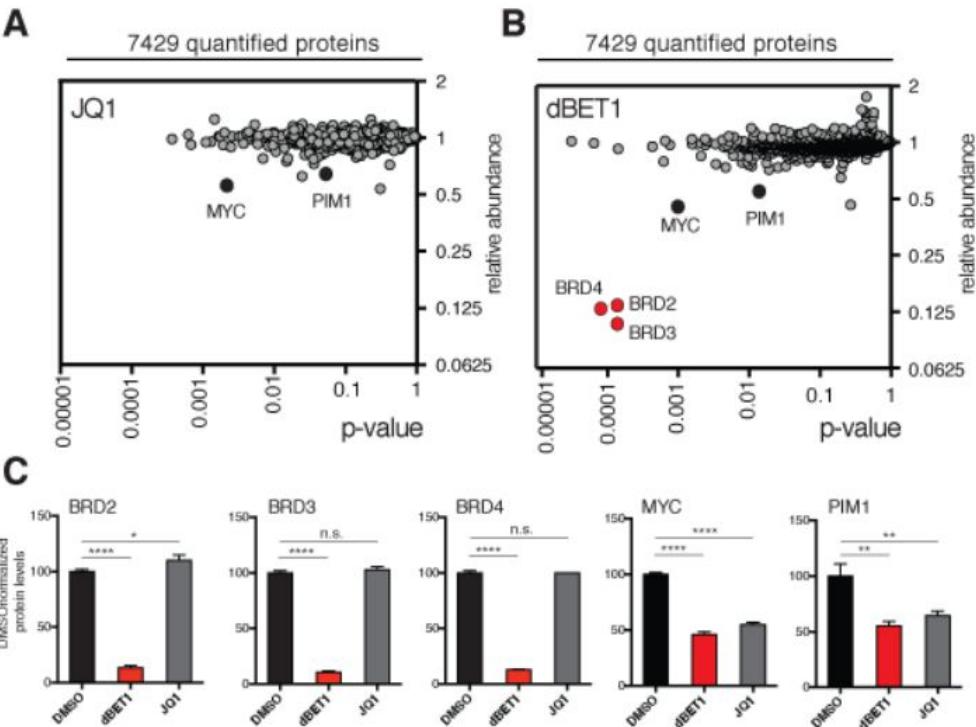
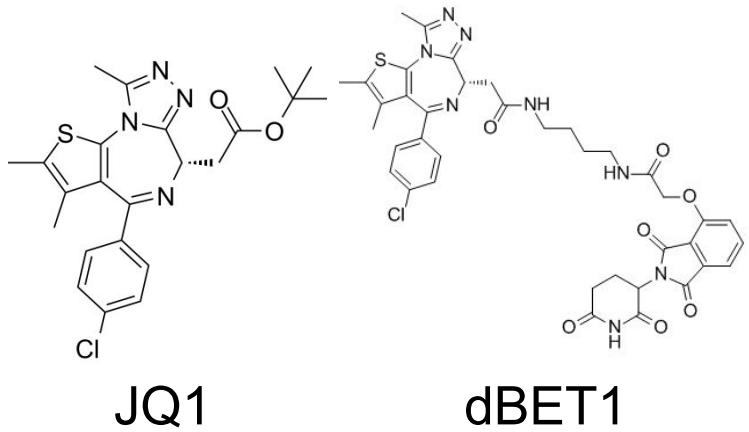
Example 1: Chemoproteomics for target ID



- Chemoproteomics methods are based on two principles: (1) **bait/prey** and (2) **competition**.
- Commonly used methods include affinity-based profiling (shown below), activity-based profiling, SILAC, etc.



Example 2: Confirmation of selective degradation of protein target *in vivo*



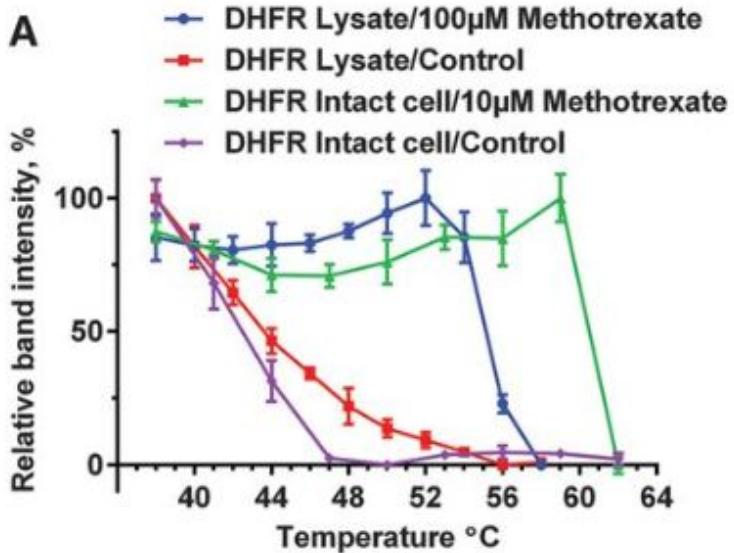
Protein stability-based methods



**DON'T EAT, NOT
EVEN COOKED!**

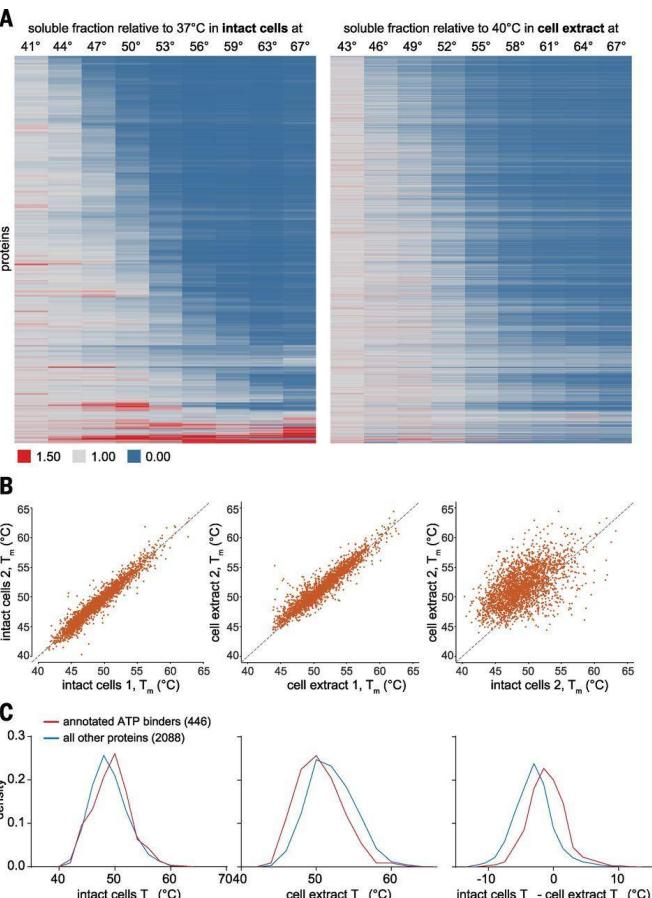
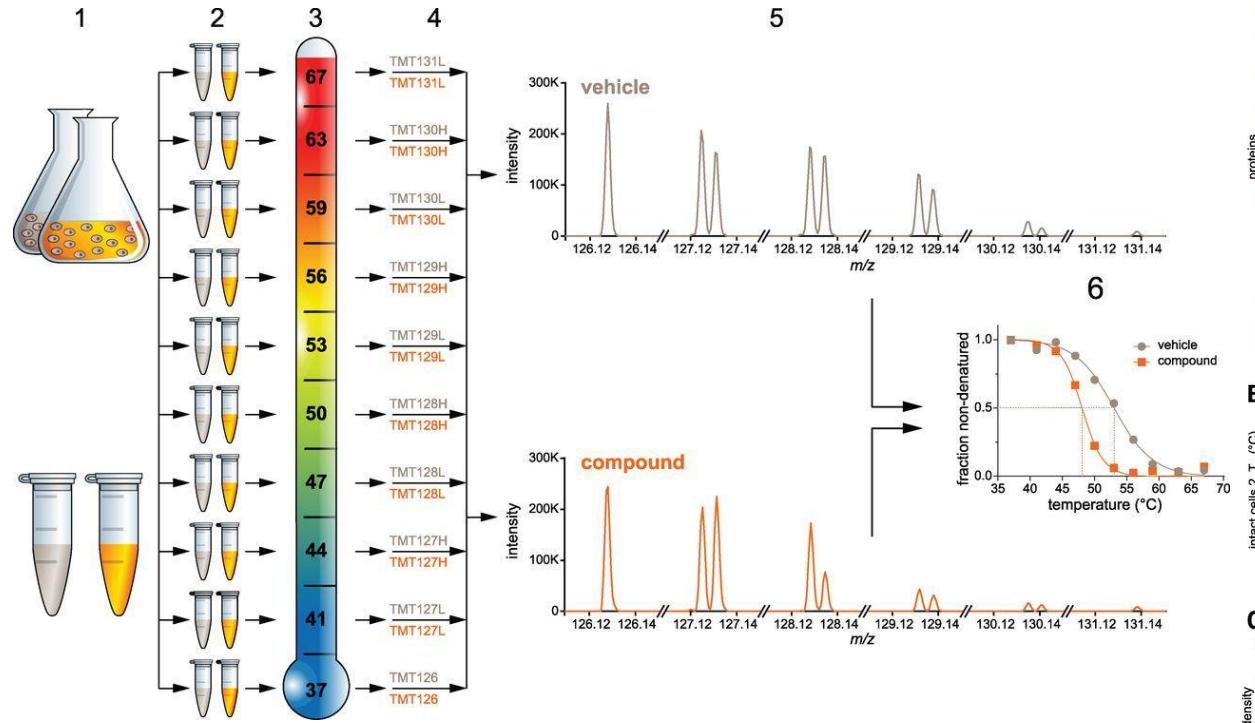
The *death cap* contains *amatoxin*, a thermal stable toxin.

Proteins are usually stabilized by ligands binding to them. This principle can be used to identify protein targets of a ligand without modification of the ligand (label-free)



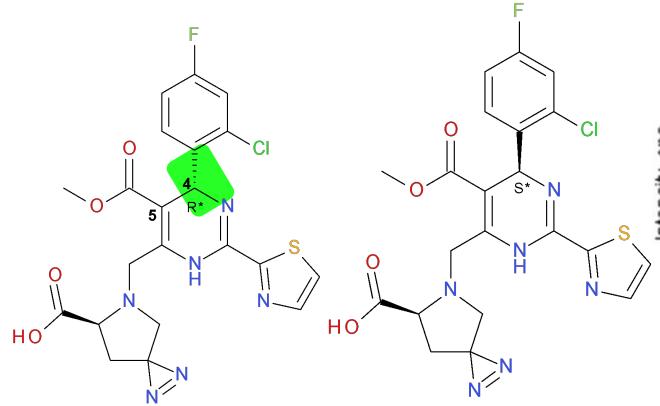
Results of Cellular Thermal Shift Assay (CETSA) to verify DHFR as a target of methotrexate.

Example 3: thermal proteome profiling to track cancer drug in living cells (CETSA)



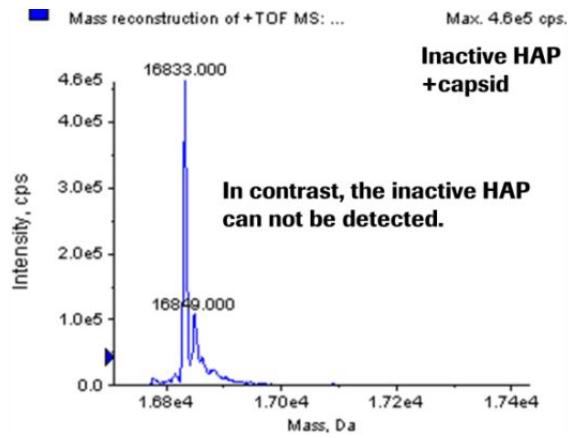
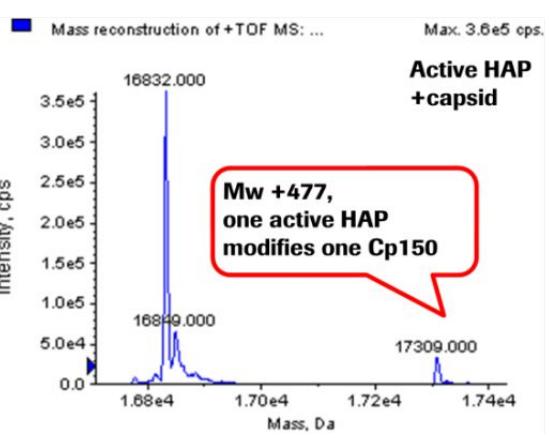
Example 4: photoaffinity labelling confirmed HBV capsid binding and mapped the small molecule binding pocket

+Cp150, UV, MS



RO-A
 EC_{50} : 0.040 μM
 IC_{50} : 0.47 μM

RO-B
 EC_{50} : >1 μM
 IC_{50} : >100 μM

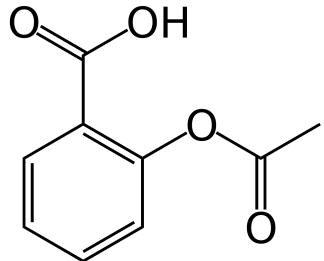


Proteolytic digestion/LC-MS/MS identified labelling site **Y118**. More photoaffinity probes identified labelling sites at **R127** and **Y38**.

Conclusions

- We predict efficacy and safety profiles of drugs by studying the mechanism and mode of action (MoA).
- Molecular modelling and (single-cell) RNA sequencing analysis are essential tools for understanding MoA of nucleotide-based modalities.
- Molecular modelling, RNA sequencing, and proteomics based on mass spectrometry (MS) are essential tools for understanding MoA of small molecules and antibodies.

The road towards MoA can be 120-year long



Dai *et al*, Cell, 2019

Acetylation blocks cGAS activity and inhibits self-DNA-induced autoimmunity



Aspirin
trademarked in
1899

- Acetylation suppresses cGAS activity
- Aspirin directly acetylates cGAS
- Aspirin inhibits cGAS-mediated interferon production
- Aspirin alleviates DNA-induced autoimmunity in AGS mouse models and patient cells

MoA understanding can be a long process full of surprises

WHEN YOU SEE A CLAIM THAT A COMMON DRUG OR VITAMIN "KILLS CANCER CELLS IN A PETRI DISH,"

KEEP IN MIND:



SO DOES A HANDGUN.

It is often easy to see what a compound does to cells or to animals.

It takes time and can be challenging to understand why it does so.

Take a deep breath, let's give it a try...

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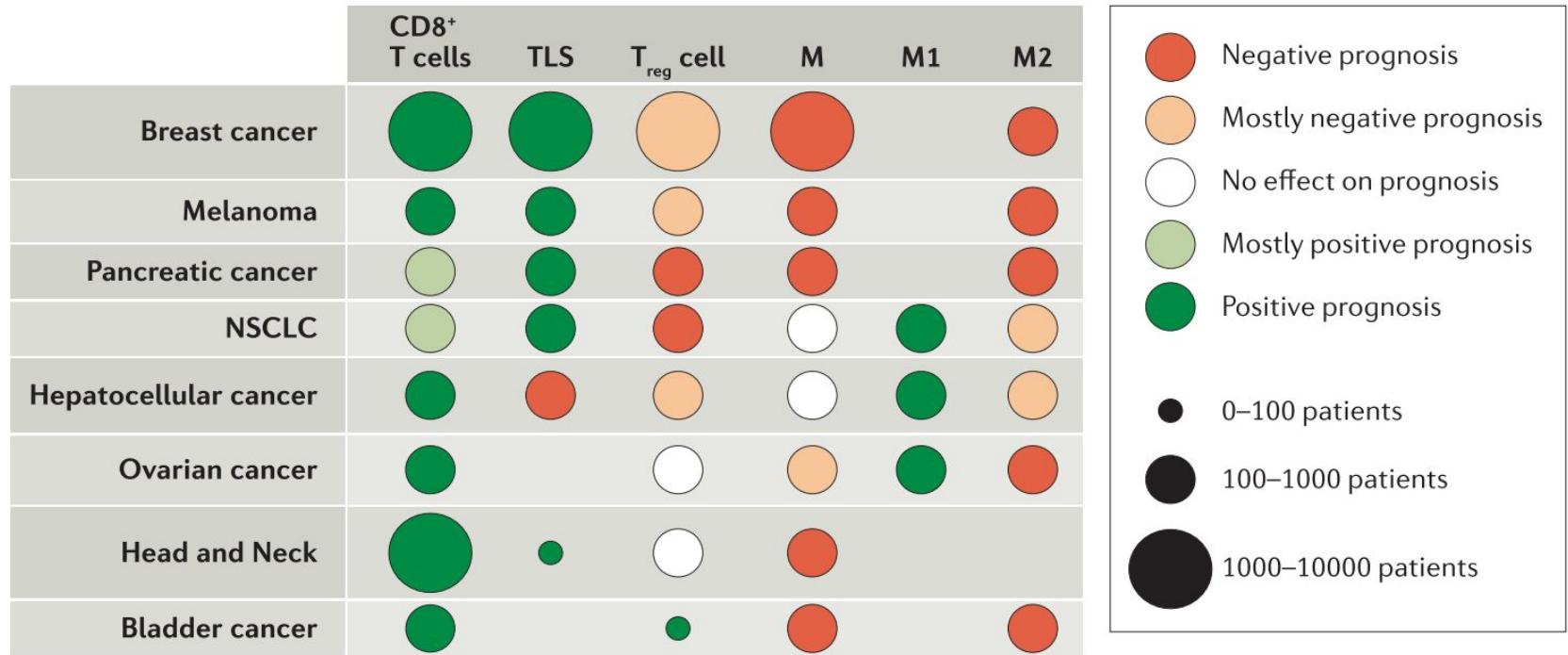
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Supplementary Information

Embryonic origins of tissues

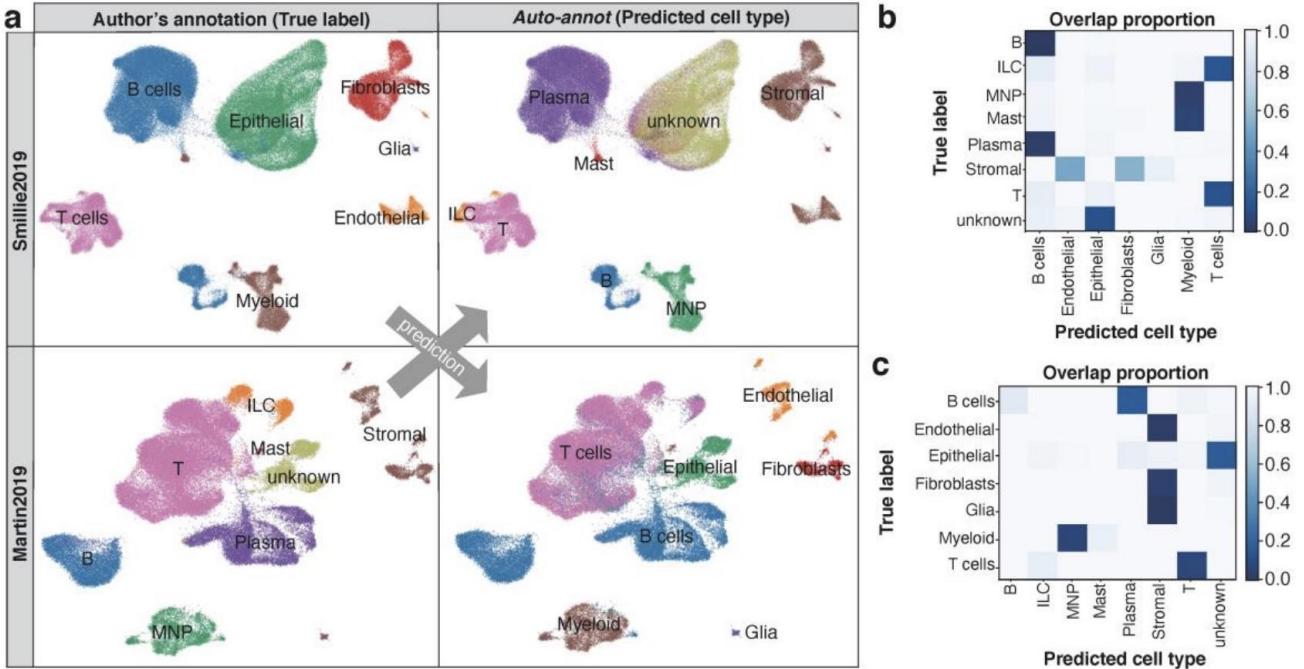
Germ Layer	Gives rise to:		
Ectoderm	Epidermis, glands on skin, some cranial bones, pituitary and adrenal medulla, the nervous system, the mouth between cheek and gums, the anus		
Mesoderm	Connective tissues proper, bone, cartilage, blood, endothelium of blood vessels, muscle, synovial membranes, serous membranes lining body cavities, kidneys, lining of gonads		
Endoderm	Lining of airways and digestive system except the mouth and distal part of digestive system (rectum and anal canal); glands (digestive glands, endocrine glands, adrenal cortex)		

Abundance of immune cells in tumor microenvironments affect outcome



TLS: tertiary lymphoid structures; T_{reg}: regulatory T cells; M: macrophages; M1/M2: subtypes of macrophages

An example of Inflammatory Bowel Disease (IBD)



We observed Inconsistent cell type nomenclature across studies.
 Machine learning allows us compare and integrate multiple studies.